Colloque MECAMAT, Rupture des Matériaux et des Structures, 21-25/01/2019

Damage and strength predictions of 3D woven composite structures: state-of-the-art and perspectives

F. Laurin, A. Hurmane, V. Medeau, J. Rannou

ONERA

THE FRENCH AEROSPACE LAB

return on innovation

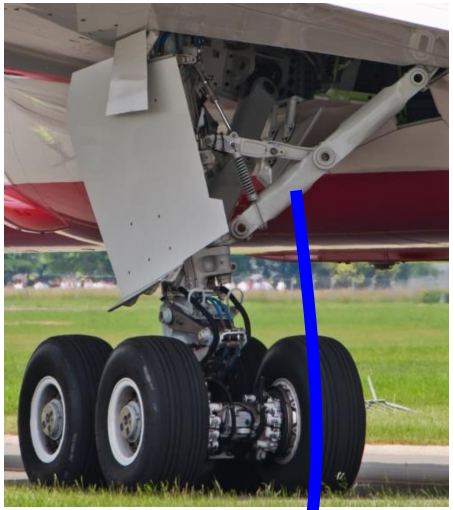
Industrial context : 3D woven composites

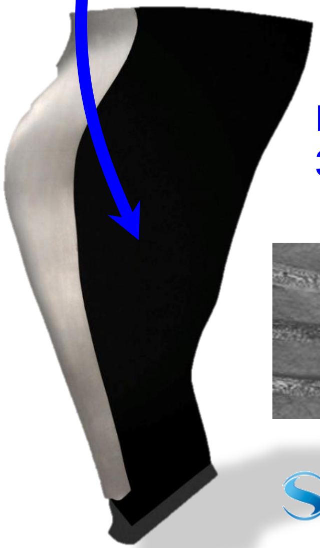
LEAP engine

Safran Aircraft Engines
Safran Landing Systems

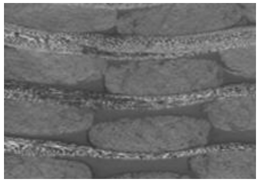
- 3D woven with polymer matrix
  - *Structures subjected to impact*
  - *Fan blade, Carter, Lug*
- Need of comprehension
  - *Recent materials, recently certified*
- Physically based model needed

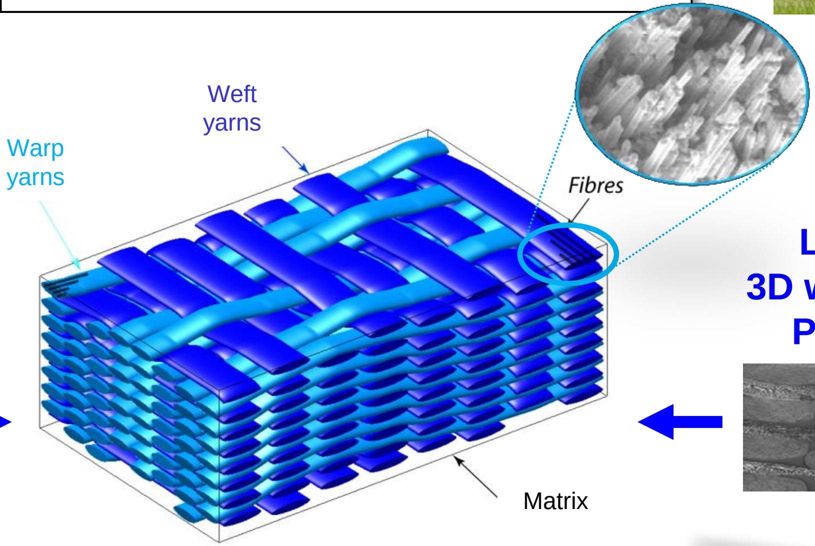
Landing gear





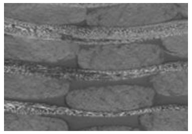
Fan blade
3D woven
PMC





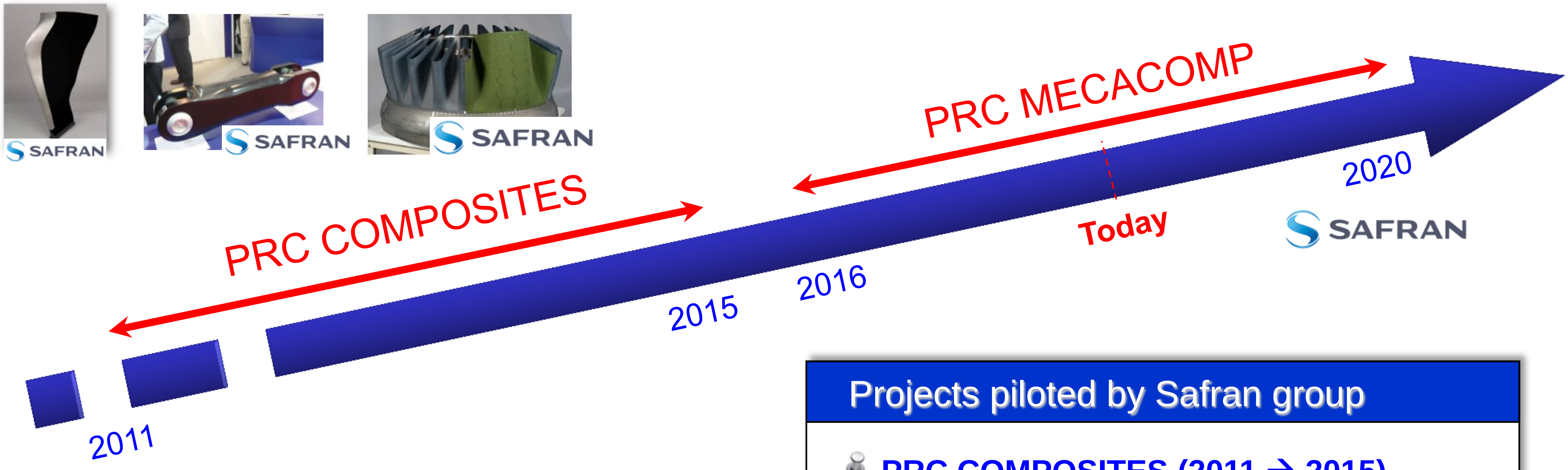
3D woven composite materials

Lug
3D woven
PMC



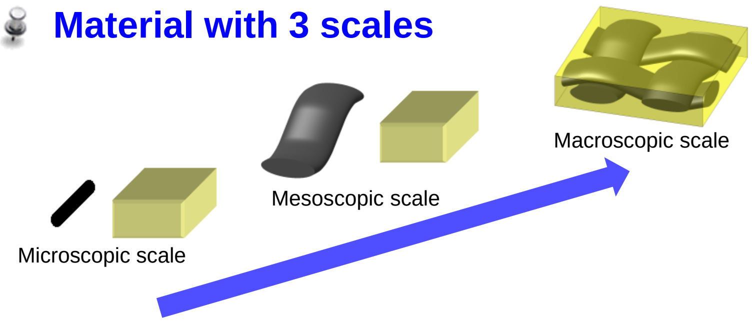
LEAP is a trademark of CFM International a
50/50 joint company between Safran Aircraft Engines and GE

Industrial context : National research projects



Multiscale composite materials

- **Material with 3 scales**



- **Macroscopic scale for design composite structures in aeronautical industries**

Projects piloted by Safran group

- **PRC COMPOSITES (2011 → 2015)**

French Research project financed by DGAC involving Safran Group, Onera and CNRS

~20 Phd-theses in different laboratories:
[Rakotoarisoa 13], [Hemon 13], [Hurmane 15], [Elias 15], [Mounien 17] …

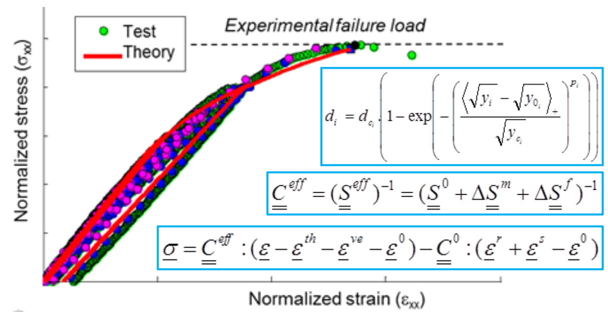
- **PRC MECACOMP (2016 → 2020)**

French Research project financed by DGAC involving Safran Group, Onera and CNRS

~20 Phd-theses in different laboratories:
[Medeau19], [Garcia 19], [Sally 20], [Archer 20] …

Three main steps for a robust design approach

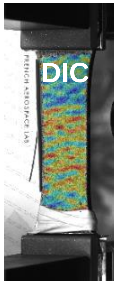
Material modelling



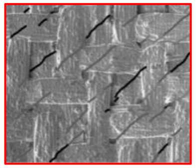
Proposition of material models

- *Damage modelling*
- *Fibre failure, softening behaviour*

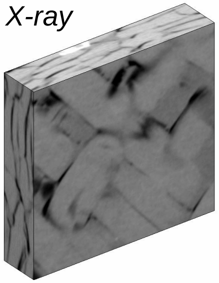
Characterization tests



SEM image



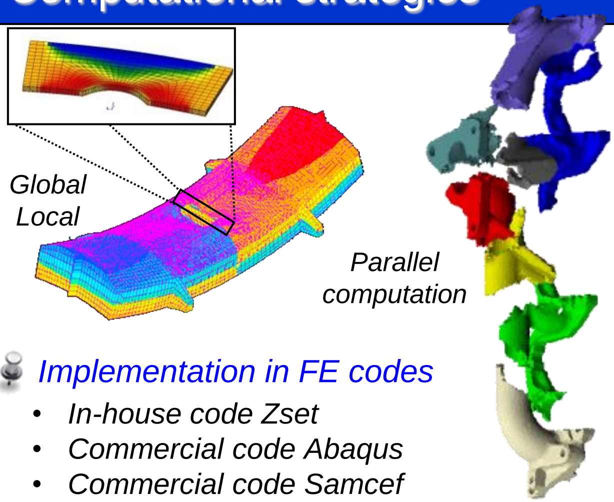
X-ray



Comprehension of ϕ mechanisms

- *Acoustic emission*
- *Digital image correlation*
- *X-Ray Tomography*

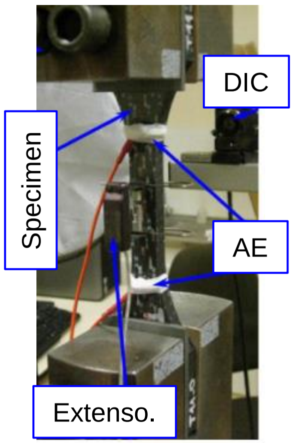
Computational strategies

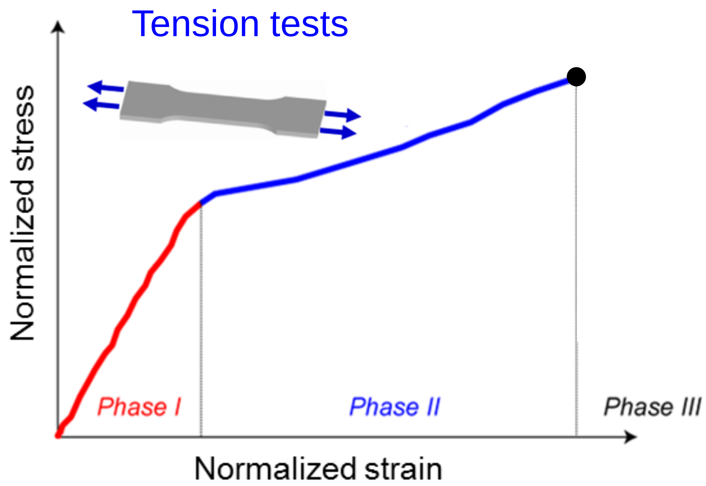


Implementation in FE codes

- *In-house code Zset*
- *Commercial code Abaqus*
- *Commercial code Samcef*

Damage and failure scenario of 3D woven composite





Multi-instrumented tests

Determination of damage scenario

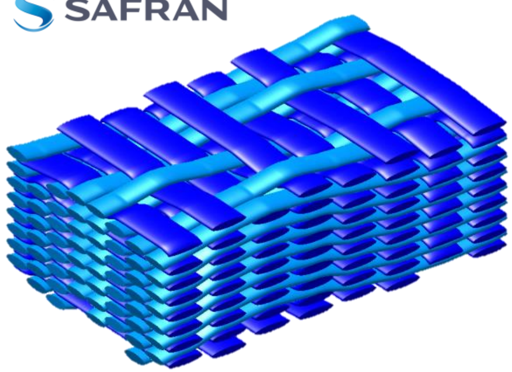
- Use of different advanced techniques
- Cross-check to ↗ confidence in data

  Strain, crack density,…
- Complementary → understand the material

  Surface, volume, …
- Matrix damage and failure mechanisms

3D woven PMC

SAFRAN

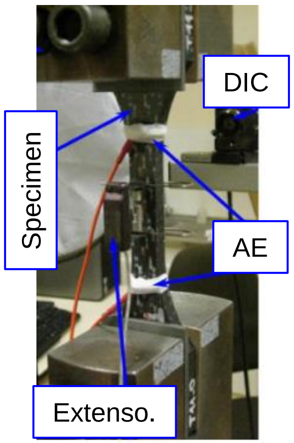


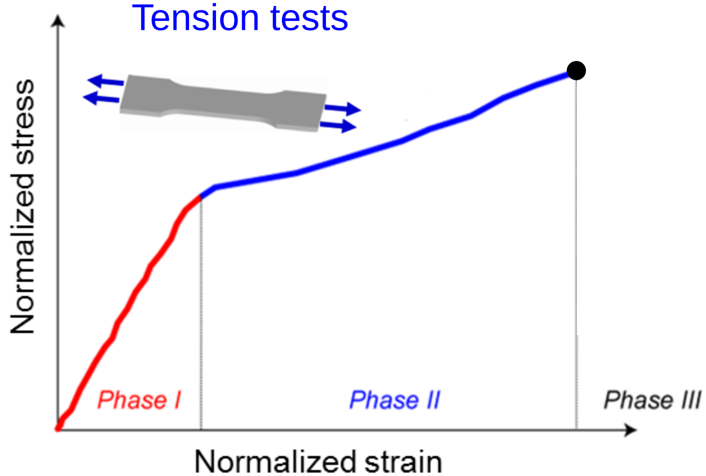
Studied material

- 3D woven composite
- Carbon / Epoxy
- Highly unbalanced 3D woven
- Large RVE

Objective: Determination of the damage scenario for different loadings

Damage and failure scenario of 3D woven composite





Multi-instrumented tests

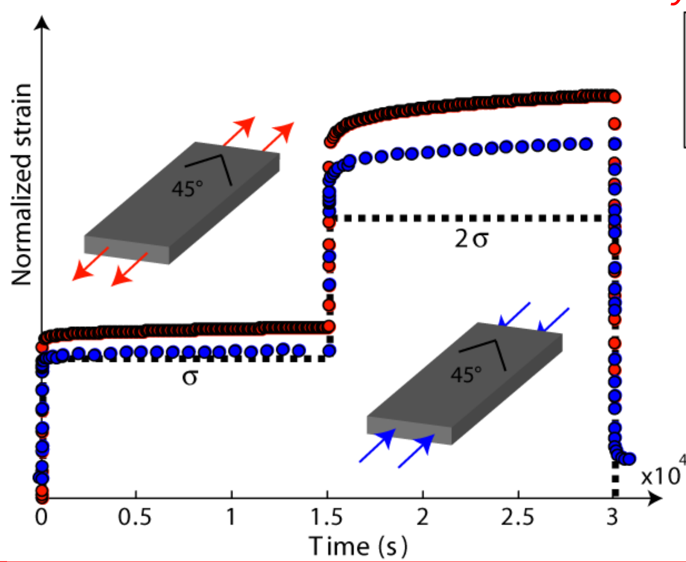
Determination of damage scenario

- Use of different advanced techniques
- Cross-check to ↗ confidence in data

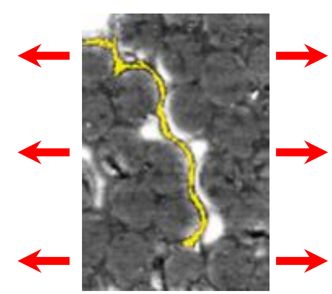
  Strain, crack density,…
- Complementary → understand the material

  Surface, volume, …
- Matrix damage and failure mechanisms

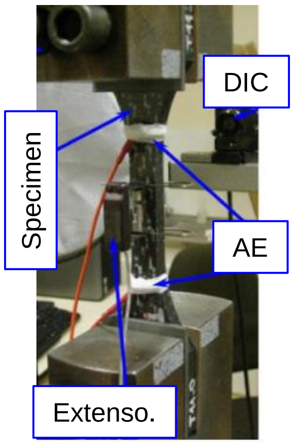
Phase I: Viscoelasticity

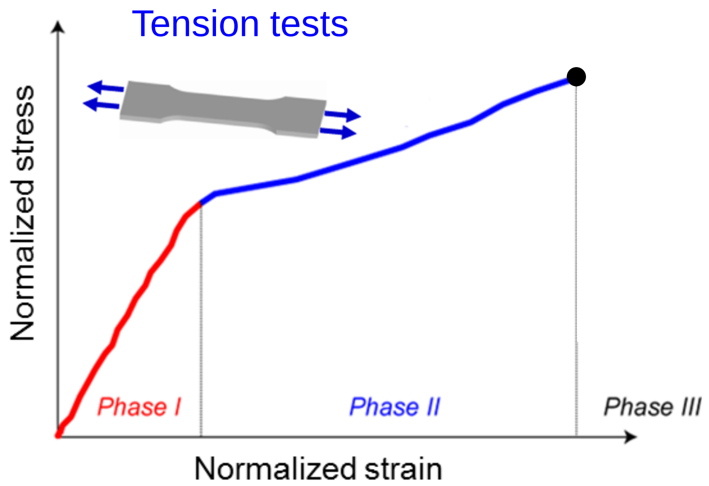


fibre/matrix deboundings



Damage and failure scenario of 3D woven composite





Multi-instrumented tests

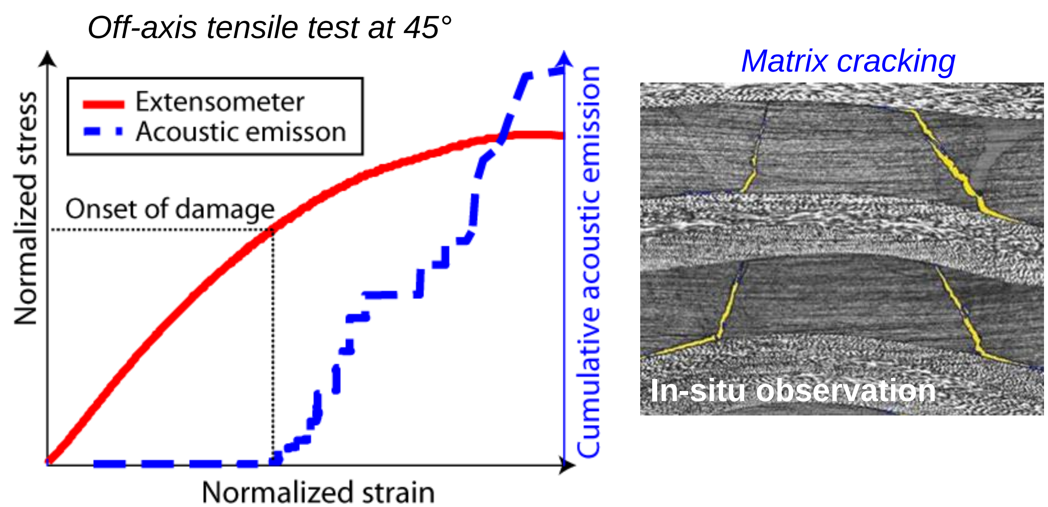
Determination of damage scenario

- Use of different advanced techniques
- Cross-check to ↗ confidence in data

  Strain, crack density,…
- Complementary → understand the material

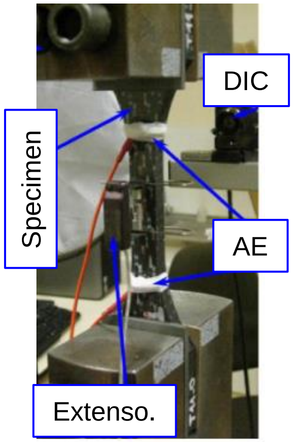
  Surface, volume, …
- Matrix damage and failure mechanisms

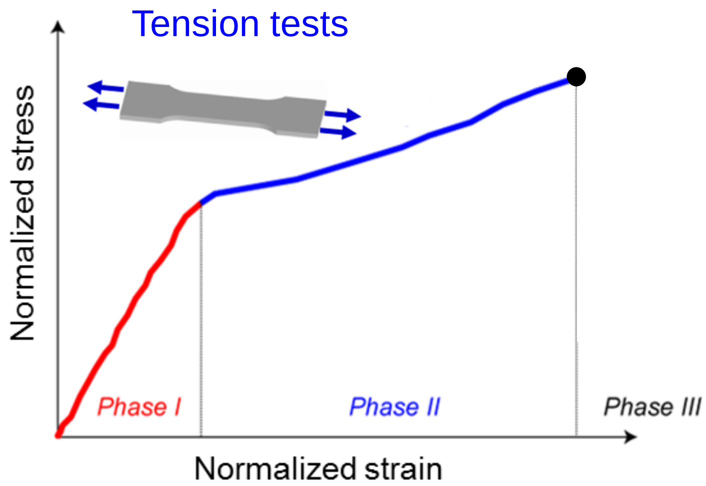
Phase II: Meso-damage



ONERA

Damage and failure scenario of 3D woven composite





Multi-instrumented tests

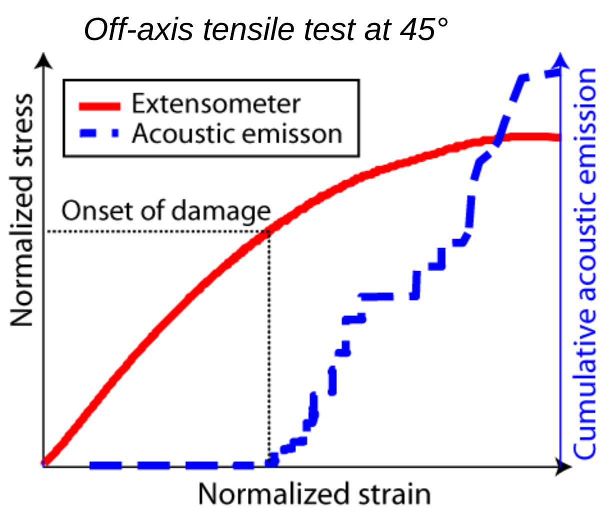
Determination of damage scenario

- Use of different advanced techniques
- Cross-check to ↗ confidence in data

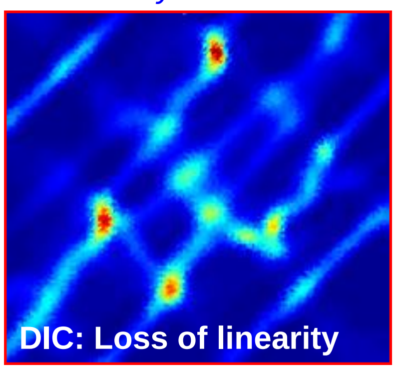
  Strain, crack density,…
- Complementary → understand the material

  Surface, volume, …
- Matrix damage and failure mechanisms

Phase II: Meso-damage

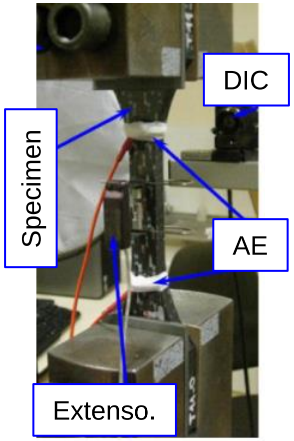


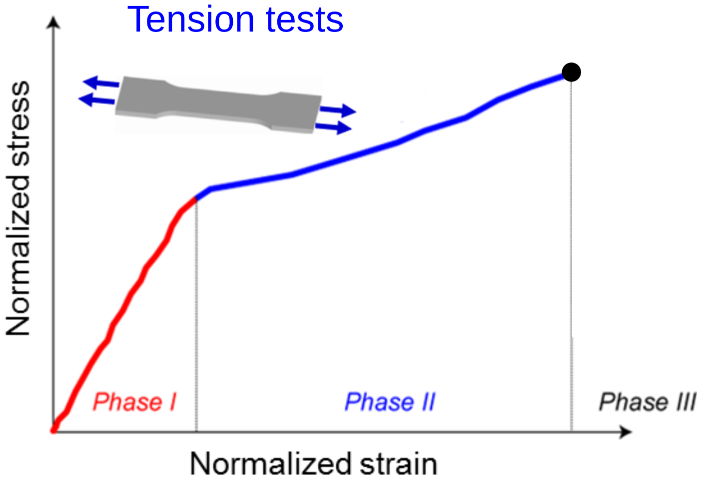
Oriented by microstructure



[Feissel 13]

Damage and failure scenario of 3D woven composite



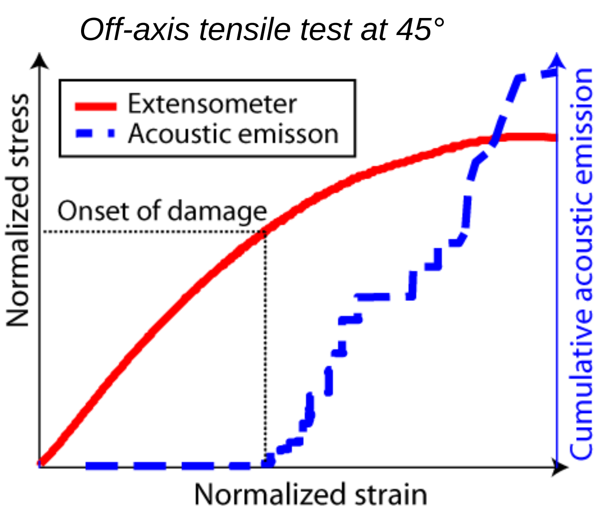


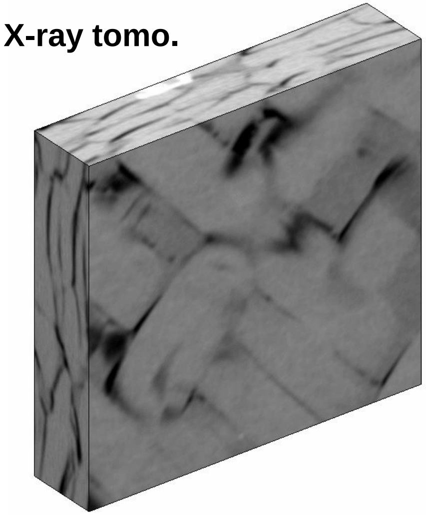
Multi-instrumented tests

Determination of damage scenario

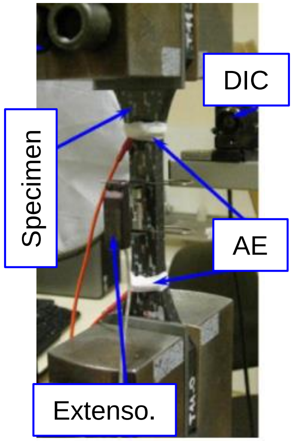
- Use of different advanced techniques
- Cross-check to ↗ confidence in data
  Strain, crack density,…
- Complementary → understand the material
  Surface, volume, …
- Matrix damage and failure mechanisms

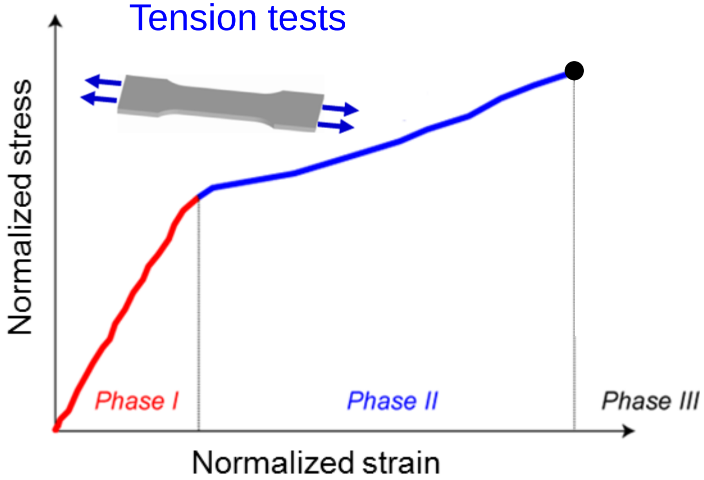
Phase II: Meso-damage





Damage and failure scenario of 3D woven composite





Multi-instrumented tests

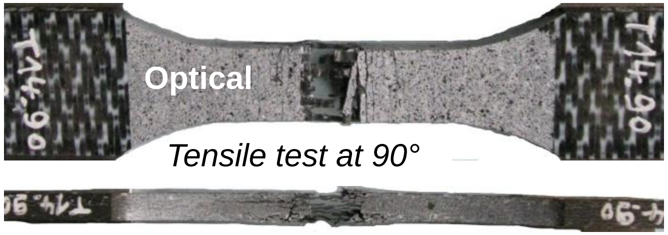
Determination of damage scenario

- Use of different advanced techniques
- Cross-check to ↗ confidence in data

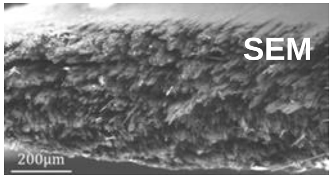
  Strain, *crack density,…*
- Complementary → understand the material

  Surface, volume, …
- Matrix damage and failure mechanisms

Phase III: failure mode



Tensile test at 90°

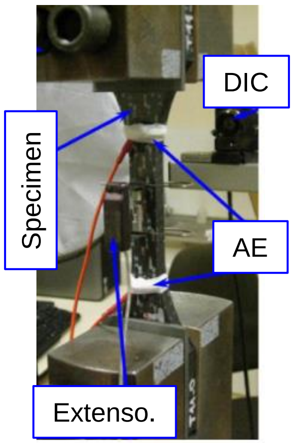


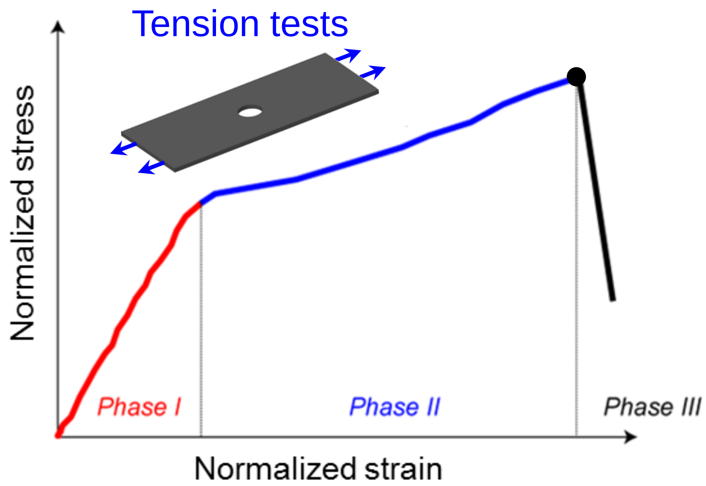
Failure pattern of weft yarn

Off-axis tensile test at 45°

Failure of fibres yarn

Damage and failure scenario of 3D woven composite





Multi-instrumented tests

Determination of damage scenario

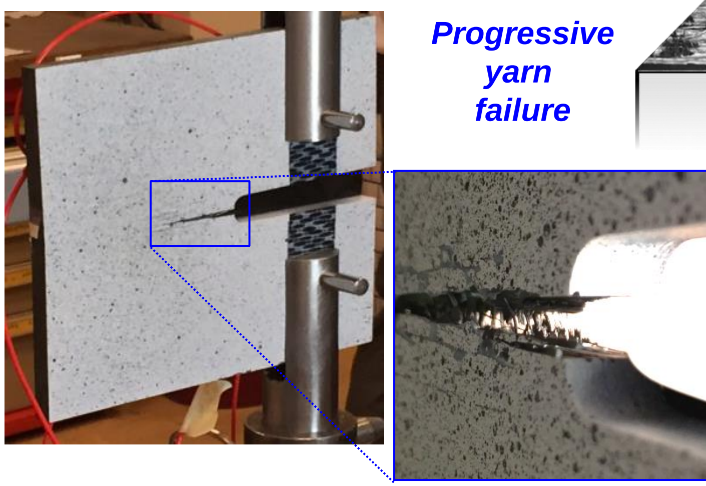
- Use of different advanced techniques
- Cross-check to ↗ confidence in data

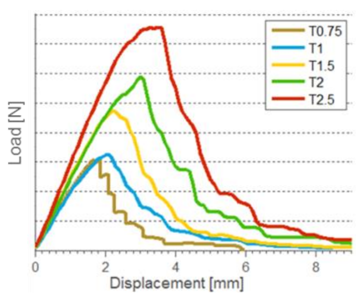
  Strain, *crack density,…*
- Complementary → understand the material

  Surface, volume, …
- Matrix damage and failure mechanisms

Phase III: failure mode

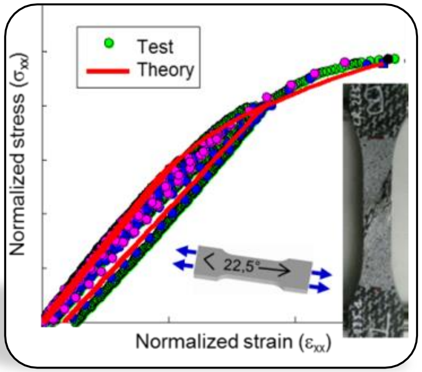
Progressive yarn failure





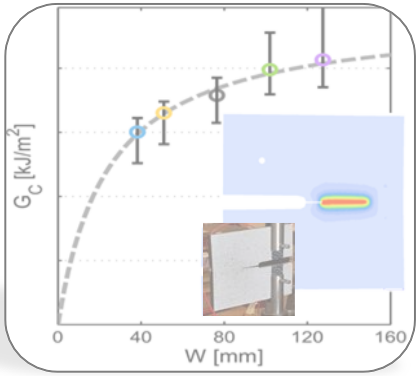
ONERA

Contents



Damage and failure model for elementary coupons

- Comprehension of the damage and failure mechanisms
- Proposition of a macroscopic damage and failure model
- Validation through comparisons with coupon tests



Strength of composite structures with singularities

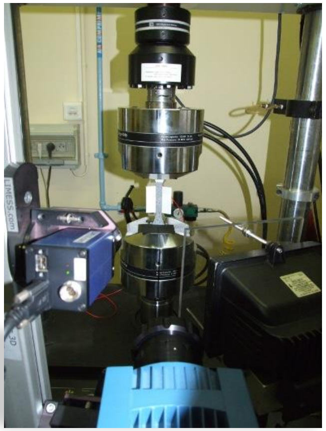
- Experimental study on progressive yarn failures
- Modelling of fibre yarn failure – physical key quantities
- Implementation of a softening behaviour in a FE code

Conclusions Perspectives	Advantages and limitations of failure approach Identification protocol – Validation tests

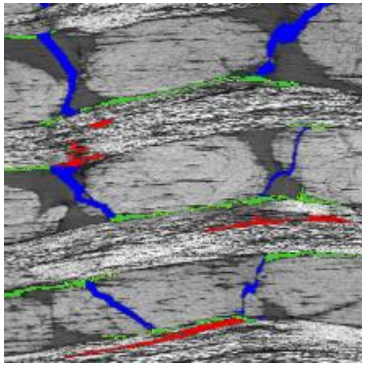
ONERA

Experimental study of damage mechanisms

static

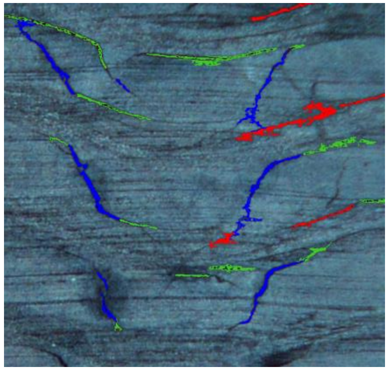


[Rakotoarisoa 13]



ONERA
THE FRENCH AEROSPACE LAB

[Henry 13]



utc
Université de Technologie Compiègne

Fatigue

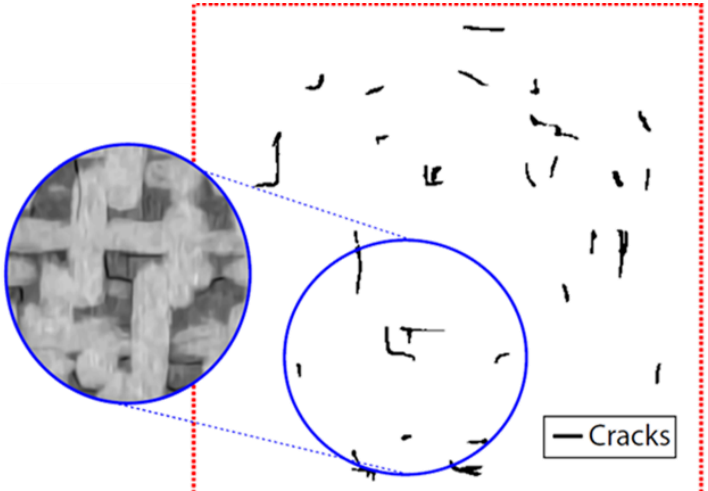
Analysis of different damage mechanisms

- Static and fatigue tests
  - Diffuse damage due to meso. architecture
  - Similar damage for static and fatigue loadings
- Impact tests (≈drop tools)
  - Diffuse damage oriented by microstructure
  - No large delamination cracks as in laminates

➡ Continuum damage models are relevant

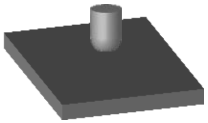
Impact

[Elias16]



X-Ray tomography

ONERA
THE FRENCH AEROSPACE LAB



Onera damage model for 3D woven composite

Mod. Test Sim.

Onera Damage and Failure Model for PMC

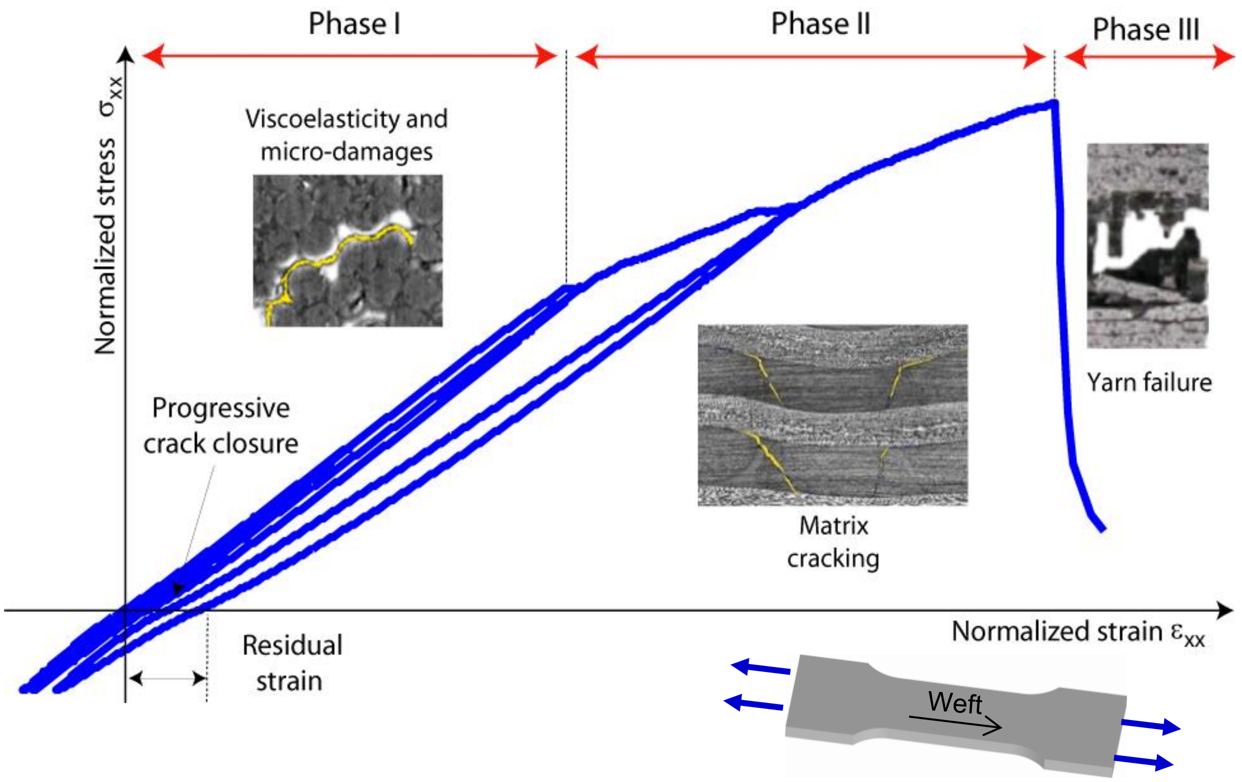
$$\underline{\sigma} = \underline{\underline{C}}^{eff} : (\underline{\varepsilon} - \underline{\varepsilon}^{th} - \underline{\varepsilon}^{ve} - \underline{\varepsilon}^{0}) - \underline{\underline{C}}^{0} : (\underline{\varepsilon}^{r} + \underline{\varepsilon}^{s} - \underline{\varepsilon}^{0})$$

with the effective compliance $\underline{\underline{C}}^{eff} = (\underline{\underline{S}}^{eff})^{-1} = (\underline{\underline{S}}^{0} + \Delta\underline{\underline{S}}^{m} + \Delta\underline{\underline{S}}^{f})^{-1}$

[Marcin 10]
[Rakotoarisoa 13]
[Hurmane 15]
[Elias 15]

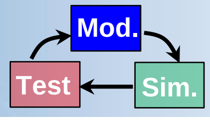
Key points

- At the macroscopic scale
- Thermodynamically consistent
- Viscoelasticity of the matrix
- Matrix damages
  - Oriented by microstructure
  - Coupling between damages
  - Stored and residual strains
- Failure of the fibre yarns
  - Oriented by microstructure
  - Softening behaviour



ONERA

Onset of damage mechanisms



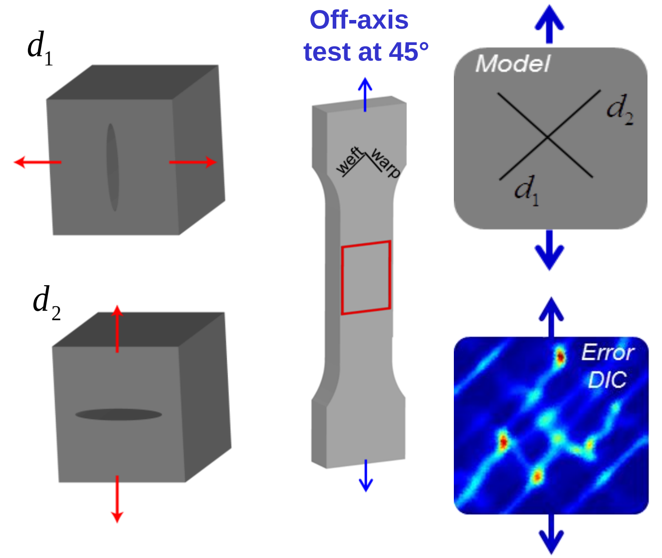
In-plane damage mechanisms

Voigt notation

- Damage oriented by architecture (2 scalar variables)
- 2 driving forces for in-plane damages

$$\begin{cases} y_1 = \dfrac{1}{2}\left(\varepsilon_1^{d_1^+} : C_{11}^0 : \varepsilon_1^{d_1^+} + a_{16}\, \varepsilon_6^{d_1^+} : C_{66}^0 : \varepsilon_6^{d_1^+} + a_{15}\, \varepsilon_5^{d_1^+} : C_{55}^0 : \varepsilon_5^{d_1^+}\right) \\ y_2 = \dfrac{1}{2}\left(\varepsilon_2^{d_2^+} : C_{22}^0 : \varepsilon_2^{d_2^+} + a_{26}\, \varepsilon_6^{d_2^+} : C_{66}^0 : \varepsilon_6^{d_2^+} + a_{24}\, \varepsilon_4^{d_2^+} : C_{44}^0 : \varepsilon_4^{d_2^+}\right) \end{cases}$$

- ε^+ used to improve predictions of onset of damage
  - Reinforcement for combined shear / compression loading



Out-of-plane damage mechanism

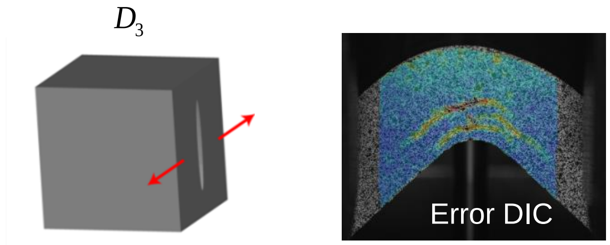
Voigt notation

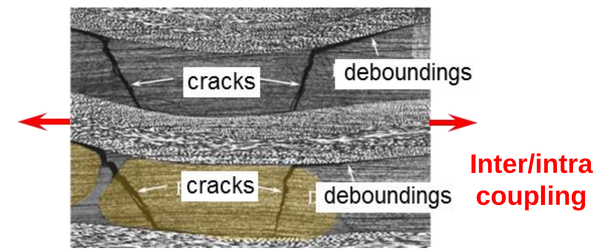
- 2 elementary thermo-dynamical forces

$$y_3 = y_3^p + y_3^{php}$$

$$\begin{cases} y_3^p = \dfrac{1}{2}\left(\varepsilon_3^{D_3^+} : C_{33}^0 : \varepsilon_3^{D_3^+} + a_{34}\, \varepsilon_4^{D_3^+} : C_{44}^0 : \varepsilon_4^{D_3^+} + a_{35}\, \varepsilon_5^{D_3^+} : C_{55}^0 : \varepsilon_5^{D_3^+}\right) \\ y_3^{php} = \dfrac{1}{2}\left(c_{31}\langle\varepsilon_1\rangle_+^2 + c_{32}\langle\varepsilon_2\rangle_+^2 + c_{36}\varepsilon_6^2\right) \end{cases}$$

- Coupling between in-plane and out-of-plane loading





Damage evolution laws and damage effects

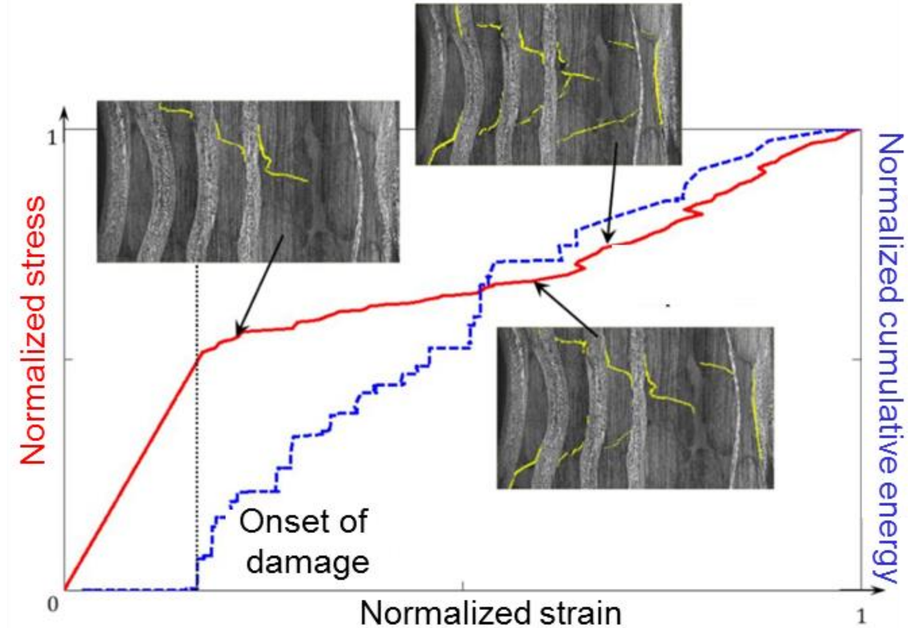
Damage evolution laws

Damage evolution laws

- Onset of damage y_0
- Saturation of damage d_c
- Evolution parameters (y_0, p)

$$d_i = d_{c_i} \cdot \left(1 - \exp\left(- \left(\frac{\left\langle \sqrt{y_i} - \sqrt{y_{0_i}} \right\rangle_+}{\sqrt{y_{c_i}}} \right)^{p_i} \right) \right)$$

- Damage can only grow $\dot{d}_i \geq 0$

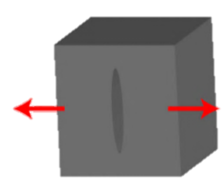


Anisotropic effect tensors

Influence on the effective compliance

$$\Delta \underline{\underline{S}}^m = \sum_i d_i \, \underline{\underline{H}}_i$$

- Depend on the elastic properties
- Determined thanks to micromechanical approach [Laws & Sih 77]

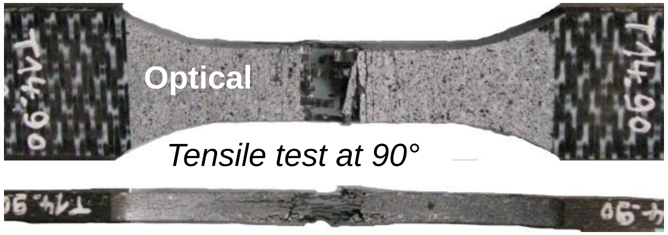


$$\underline{\underline{H}}_1^+ = \begin{pmatrix} h_{11}^{1+} S_{11}^0 & 0 & 0 & 0 & 0 & 0 \\ & 0 & 0 & 0 & 0 & 0 \\ & & 0 & 0 & 0 & 0 \\ & & & 0 & 0 & 0 \\ & sym. & & & h_{55}^{1+} S_{55}^0 & 0 \\ & & & & & h_{66}^{1+} S_{66}^0 \end{pmatrix}$$

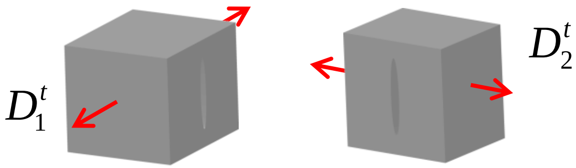
Failure mechanisms

Tension failure of fibre yarns

- Failure cracks are oriented by the microstructure (failure of fibre yarns)
- 2 scalar failure variables *(D_1^t,D_2^t)*
  - Driving forces $y_1^{D+} = \frac{1}{2} C_{11}^0 \langle \varepsilon_1 \rangle_+^2$ and $y_2^{D+} = \frac{1}{2} C_{22}^0 \langle \varepsilon_2 \rangle_+^2$



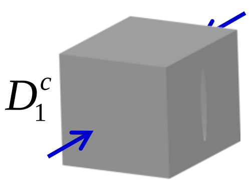
[Hurmane 15]

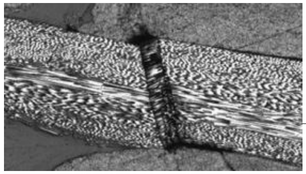


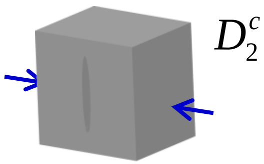
Compression failure of fibre yarns

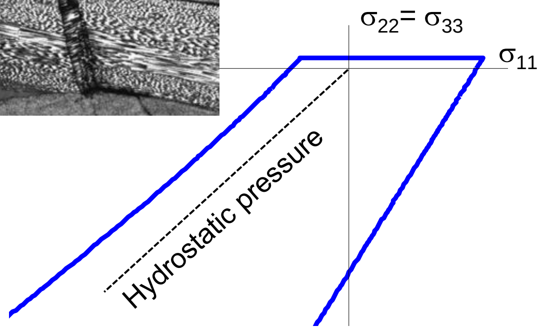
- Failure cracks are oriented by the microstructure (orientation of fibre yarns)
- 2 scalar failure variables *(D_1^c,D_2^c)*
  - Driving forces
$$\begin{cases} y_1^{D-} = \sqrt{\langle \sigma_1 - \sigma_3 \rangle_+^2 + a_1^t \tau_{13}^2} \\ y_2^{D-} = \sqrt{\langle \sigma_2 - \sigma_3 \rangle_+^2 + a_2^t \tau_{23}^2} \end{cases}$$
- Influence of the hydrostatic pressure
  - No possible failure if $\sigma_{11}=\sigma_{22}=\sigma_{33}$ compression
- Influence of the out-of-plane shears

[Elias 15]

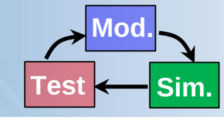






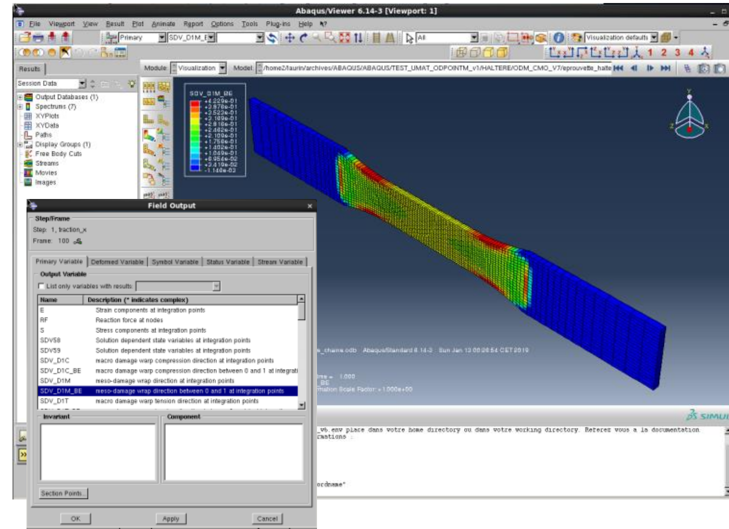


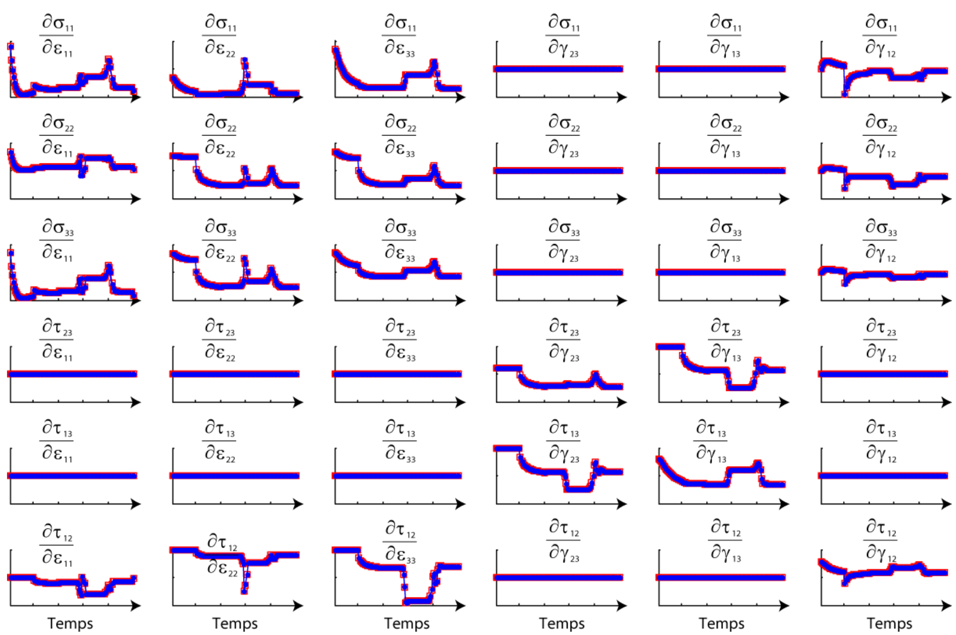
ONERA

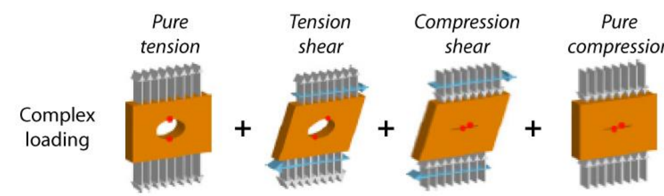


Implementation in FE codes

- **Implementation in different FE Codes**
  - Available in different commercial finite element codes with implicit solver
- **Definition of variables useful in design offices**
  - Proposition of driving forces and damage variables simple to analyse (evolving between 0 and 1)





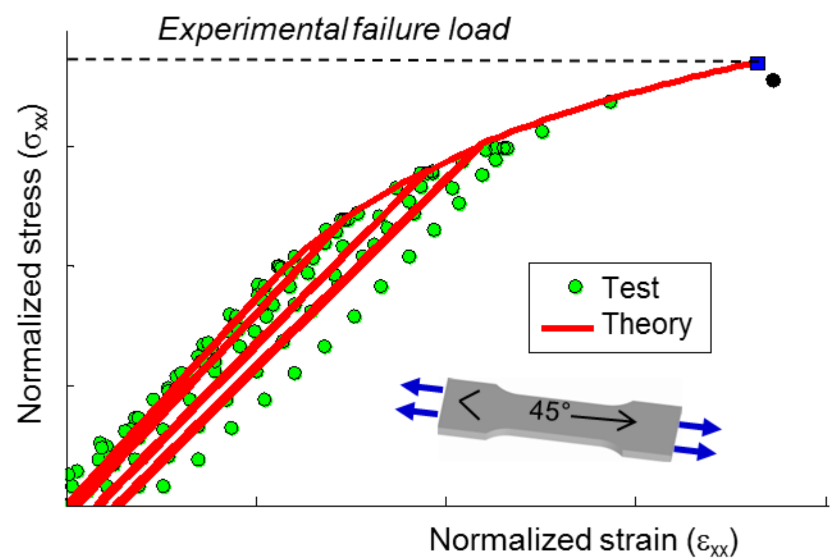


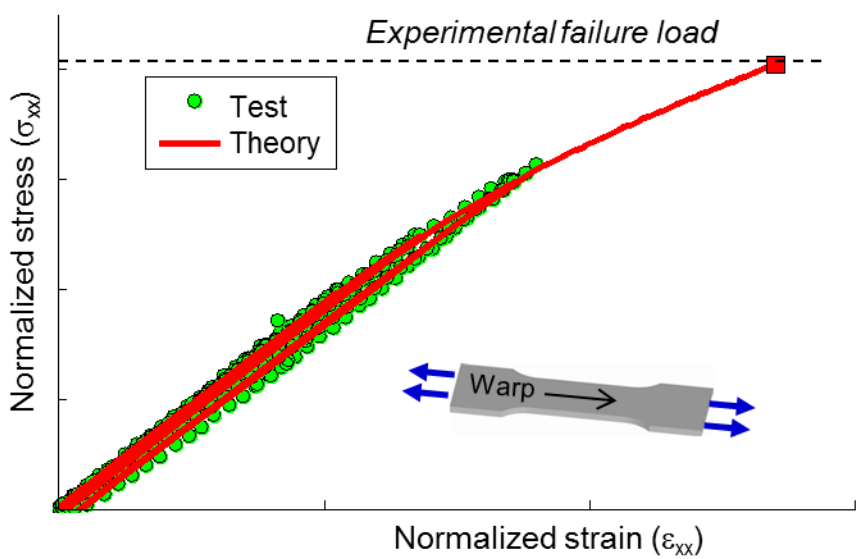
- **Special care to the accuracy of the consistent tangent matrix**
  - Validation thanks to cross-check with numerical solution on 51 test cases (perturbation method)
  - Non symmetrical 4th order tensor

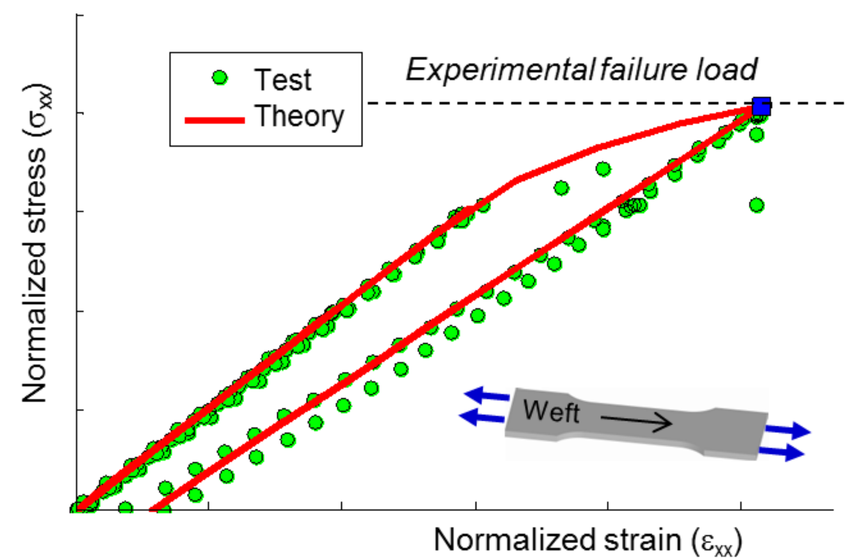
Comparisons with static test results

Conclusions

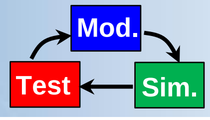
- Off-axis tensile tests at different angles
  - Multi-instrumented incremental tensile tests at 0°, 22.5°, 45°, 67.5° and 90° performed at Onera
  - *[Rakotoarisoa 11], [Elias 15]*
- Predictions are in good agreement with the available test results
  - Evolution of the apparent moduli, effects of crack closure, residual strain and failure predictions





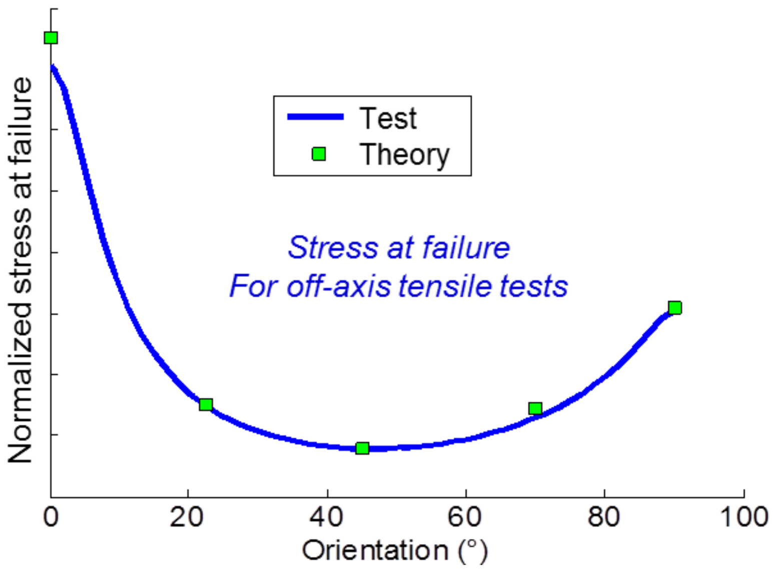


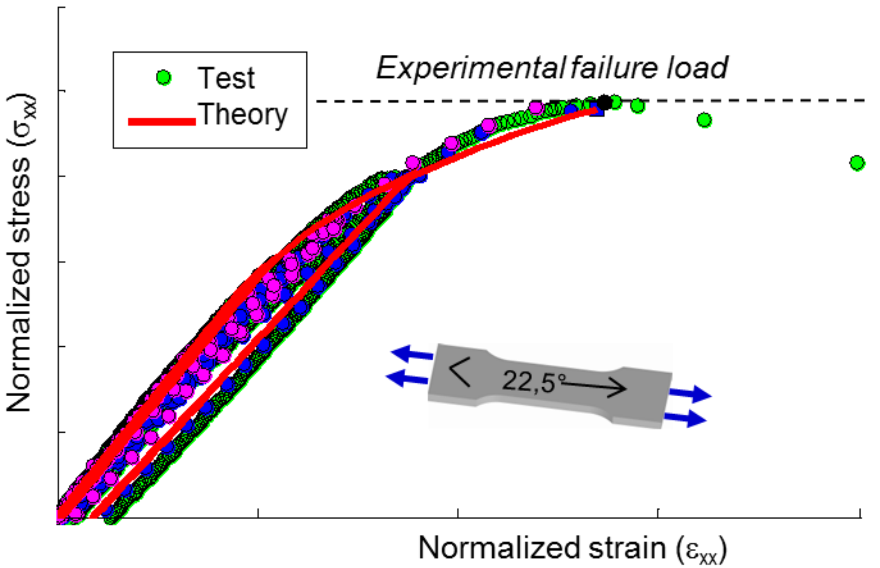
Comparisons with static test results

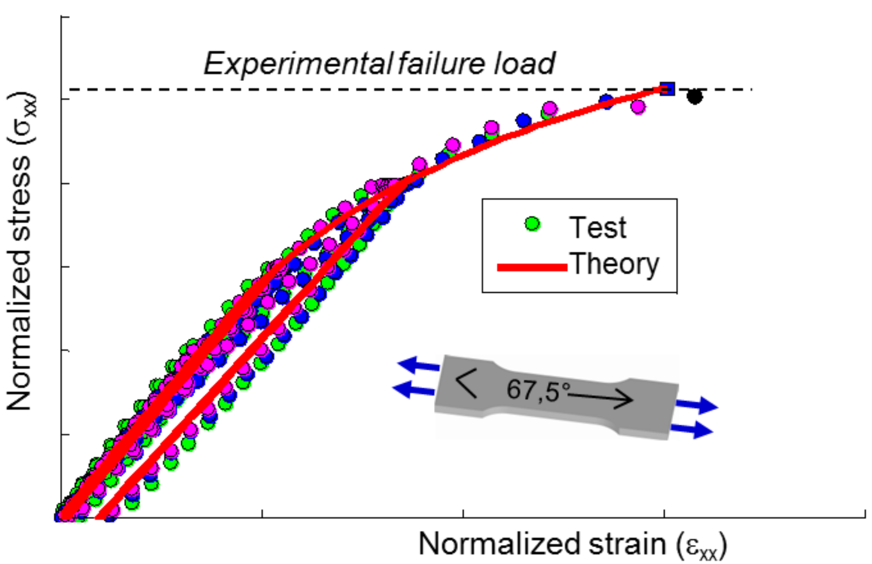


Conclusions

- Off-axis tensile tests at different angles
  - Multi-instrumented incremental tensile tests at 0°, 22.5°, 45°, 67.5° and 90° performed at Onera
  - *[Rakotoarisoa 11], [Elias 15]*
- Predictions are in good agreement with the available test results
  - Evolution of the apparent moduli, effects of crack closure, residual strain and failure predictions







Comparisons with low velocity impact tests

Extension to impact problems

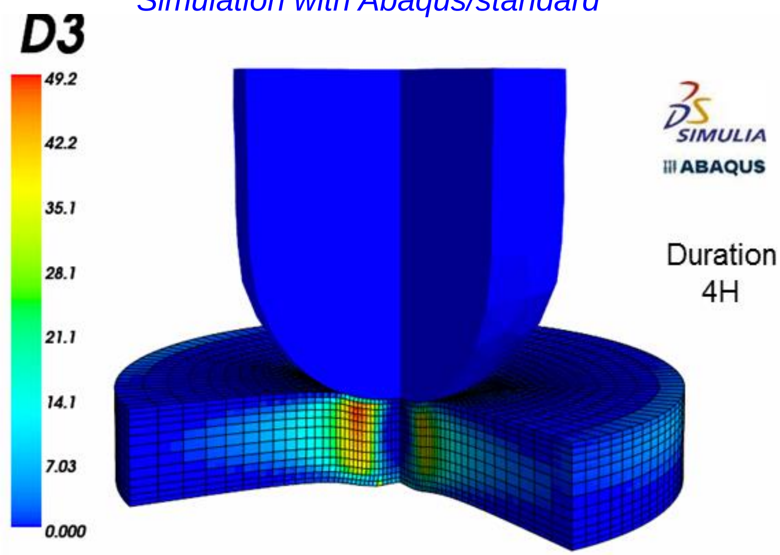
Simulation of impact tests

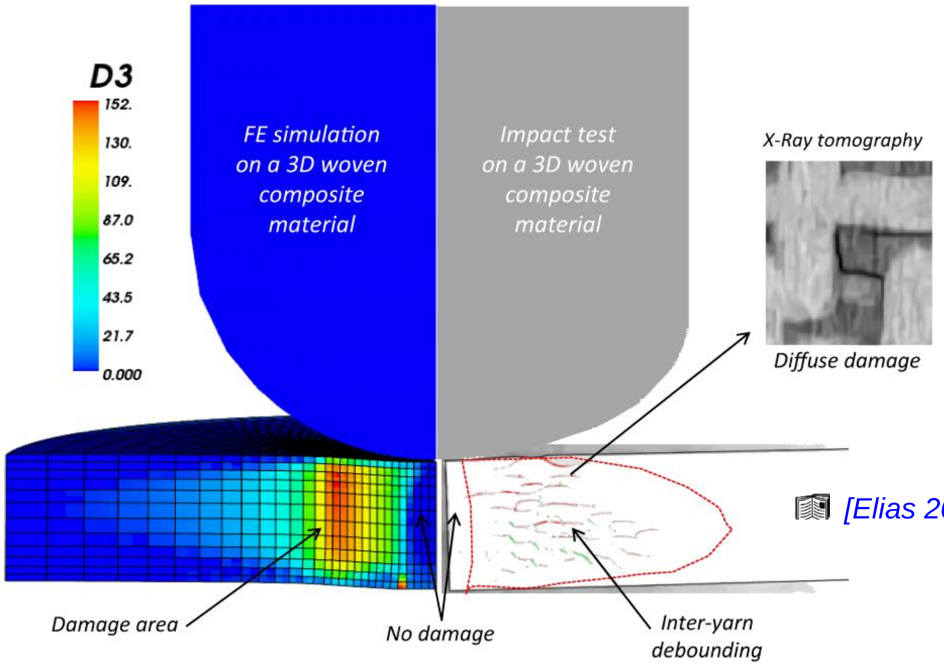
- Simulation with abaqus/standard *(implicit solver)*
- Robust and efficient modelling (few hours)

Comparisons with test results

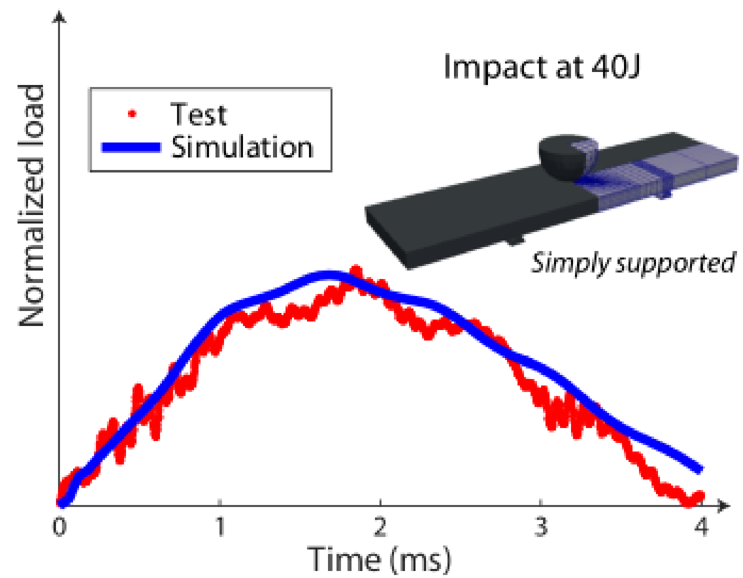
- Accurate predictions of load/time curves for different impact energies
- Accurate estimation of damage patterns through the thickness of the specimens

Simulation with Abaqus/standard





[Elias 2017]

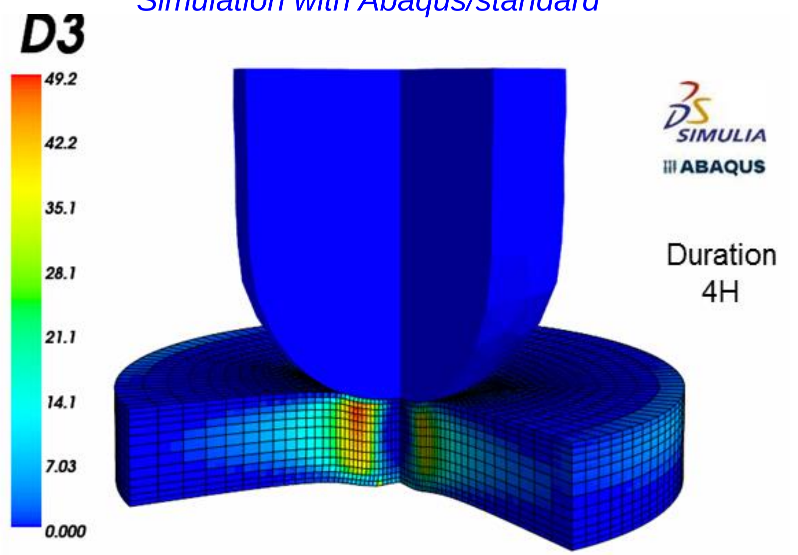


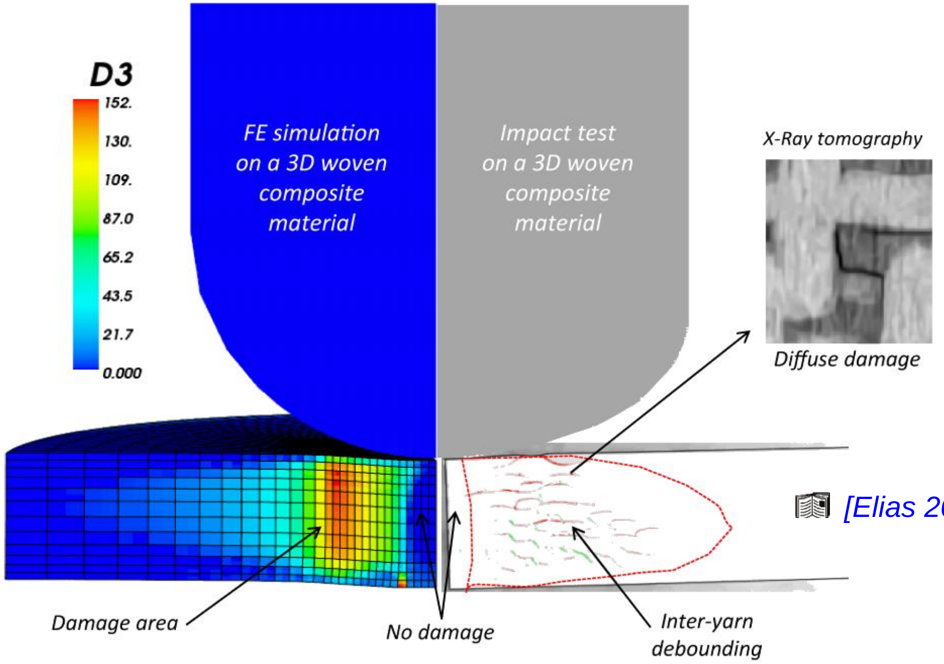
Mod. Test Sim.

Extension to impact problems

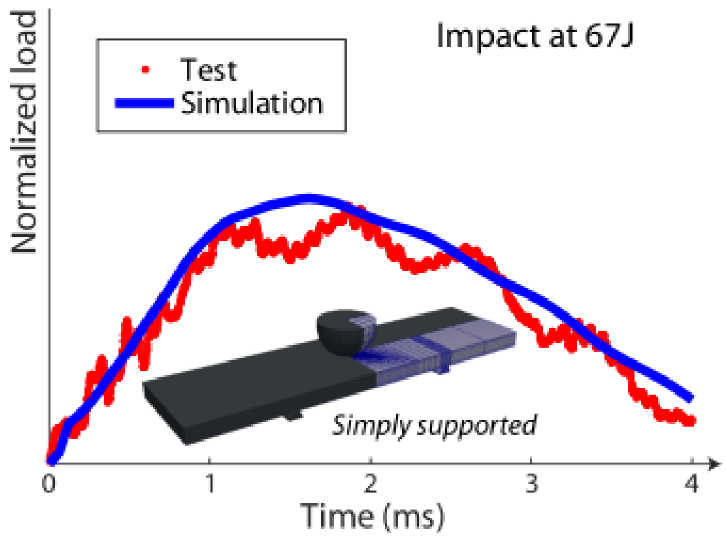
- Simulation of impact tests
  - Simulation with abaqus/standard *(implicit solver)*
  - Robust and efficient modelling (few hours)
- Comparisons with test results
  - Accurate predictions of load/time curves for different impact energies
  - Accurate estimation of damage patterns through the thickness of the specimens

Simulation with Abaqus/standard





[Elias 2017]



ONERA

Comparisons with low velocity impact tests

Extension to impact problems

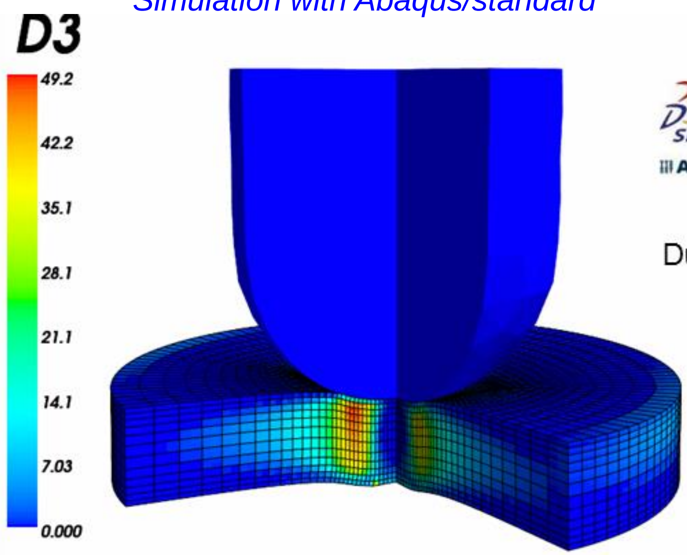
Simulation of impact tests

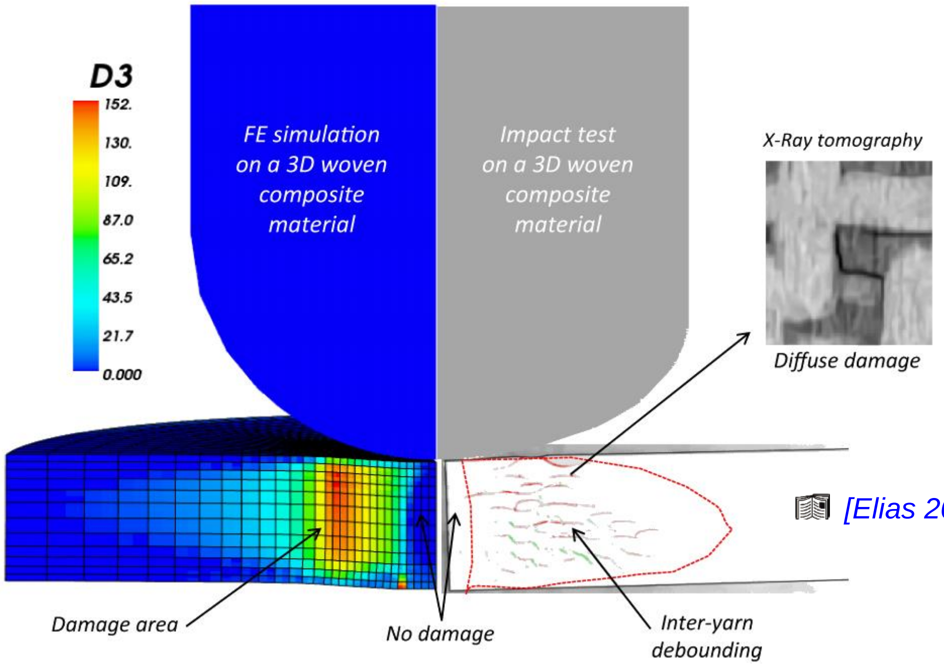
- Simulation with abaqus/standard *(implicit solver)*
- Robust and efficient modelling (few hours)

Comparisons with test results

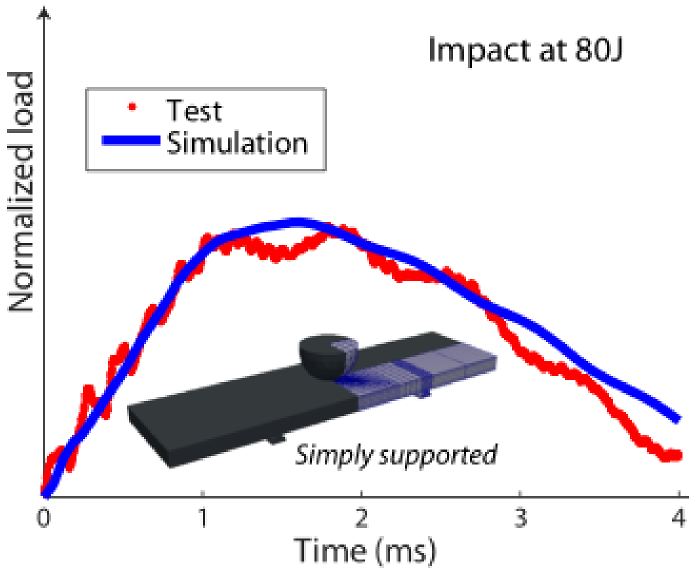
- Accurate predictions of load/time curves for different impact energies
- Accurate estimation of damage patterns through the thickness of the specimens

Simulation with Abaqus/standard

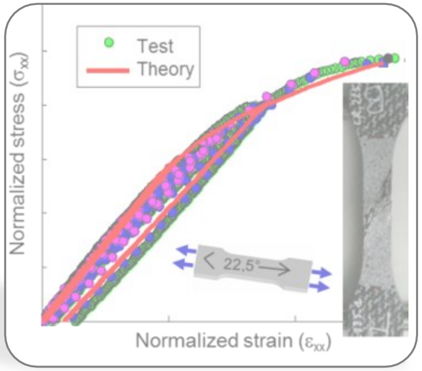




[Elias 2017]

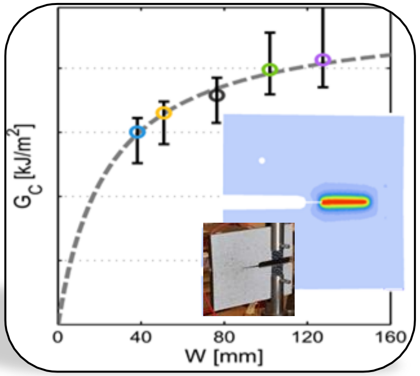


Contents



Damage and failure model for elementary coupons

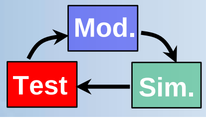
- Comprehension of the damage and failure mechanisms
- Proposition of a macroscopic damage and failure model
- Validation through comparisons with tests



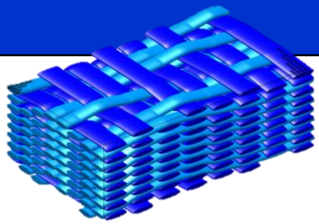
Strength of composite structures with singularities

- Experimental study on progressive yarn failures
- Modelling of fibre yarn failure – physical key quantities
- Implementation of a softening behaviour in a FE code

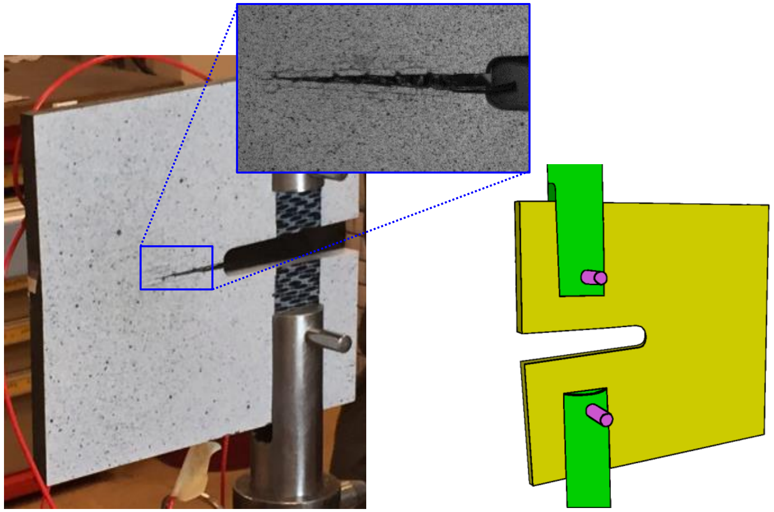
Conclusions Perspectives	Advantages and limitations of failure approach Identification protocol – Validation tests



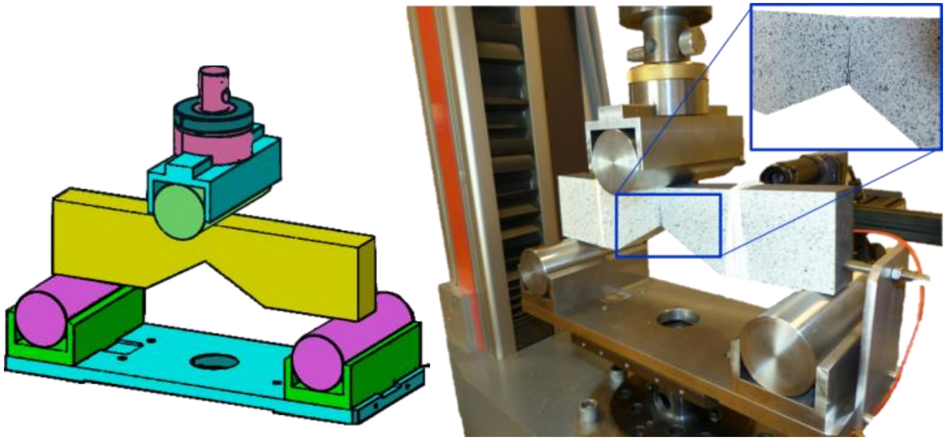
Presentation of the test campaign



- Test configurations with stable crack propagation
  - 3D highly unbalanced woven material tested in the weft direction
  - Identification of the *critical energy release rate* G_c for fibre yarn failure
    - Compact Tension test (CT) *[ASTM E1922-04], [Pinho 06], [Laffan10], [Bergan 16]*
    - Single Edge Notched Beam (SENB) *[ASTM 5045-99]*
  - Design of specimens with specificities of 3D woven composites *[Blanco 14]*
- Size effect for CT specimens (5 different sizes with a constant thickness)

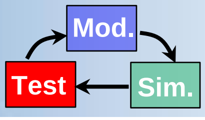


Configuration of the standard CT test

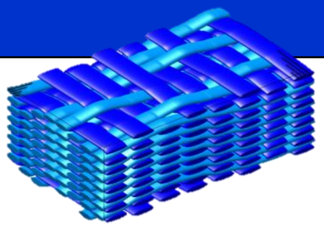


Configuration of the standard SENB test

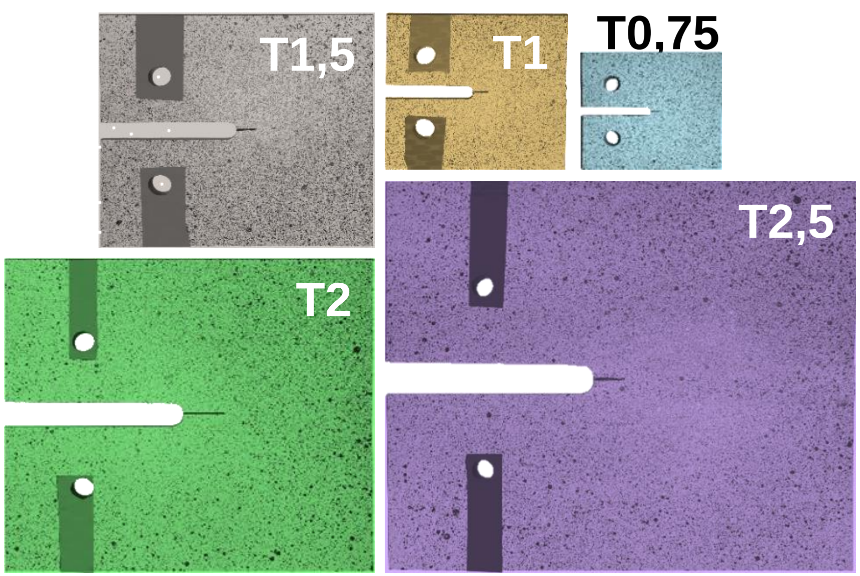
Experimental study of fibre yarn failure mechanisms



Presentation of the test campaign



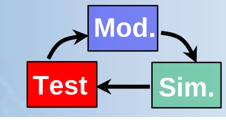
- Test configurations with stable crack propagation
  - 3D highly unbalanced woven material tested in the weft direction
  - Identification of the *critical energy release rate* G_c for fibre yarn failure
    - Compact Tension test (CT) *[ASTM E1922-04], [Pinho 06], [Laffan10], [Bergan 16]*
    - Single Edge Notched Beam (SENB) *[ASTM 5045-99]*
  - Design of specimens with specificities of 3D woven composites *[Blanco 14]*
- Size effect for CT specimens (5 different sizes with a constant thickness)



Homothetic CT specimens

SENB specimen

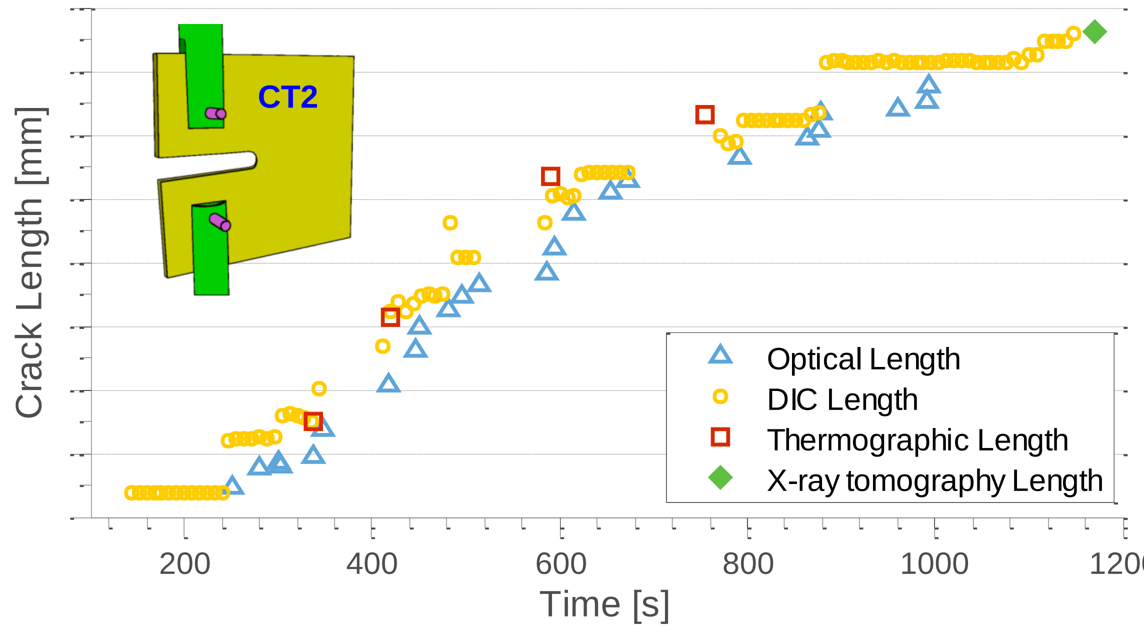
Measurement of macroscopic crack propagation



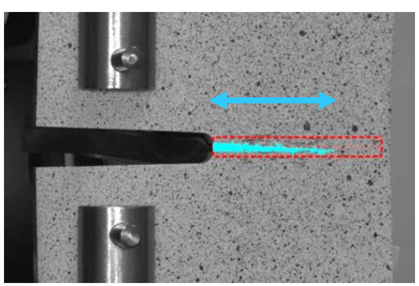
Crack propagation

- Different measurement techniques
  - Optical tracking *(grey level gradient)*
  - DIC tracking *(discontinuity disp. field)*
  - IR thermography *(heating crack)*
  - X-Ray tomography *(ex and in-situ)*
- Different measurement techniques
  - Cross-check to ↗ confidence
  - Complementary technique

    Surface, volume, …

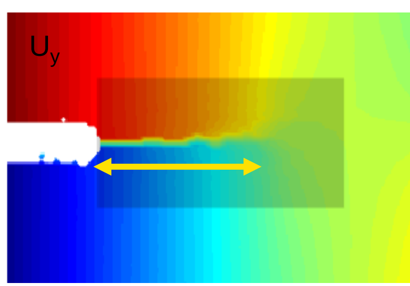


Optical tracking



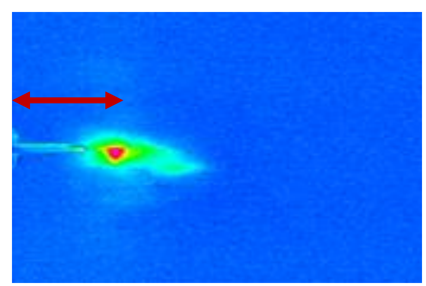
📖 *[Pack 17]*
[Panin 17]

DIC tracking



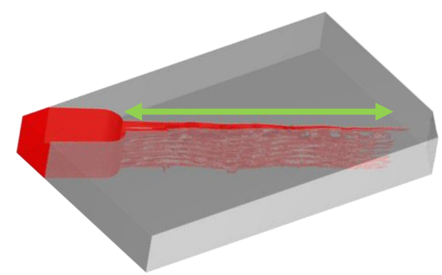
📖 *[Lopez-Crespo 08]*
[Vanlanduit 09]
[Catalanotti 10]

IR Thermography



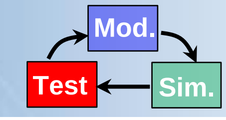
📖 *[Muller 16]*
[Archer 17]

X-ray Tomography



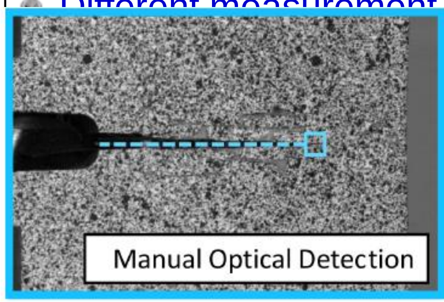
X-Ray tomography by
Safran Aircraft Engines

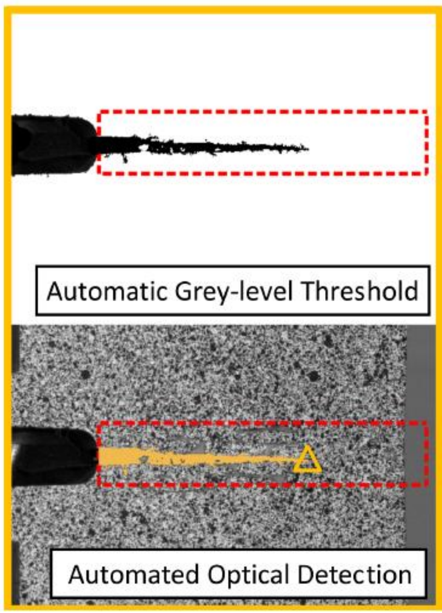
Measurement of macroscopic crack propagation

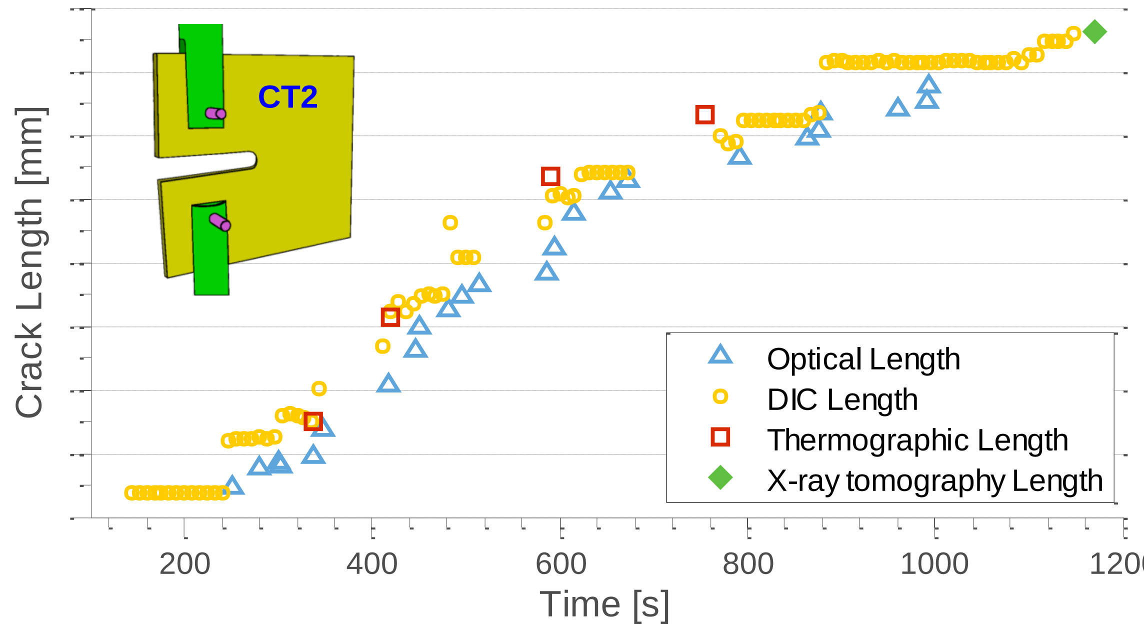


Crack propagation

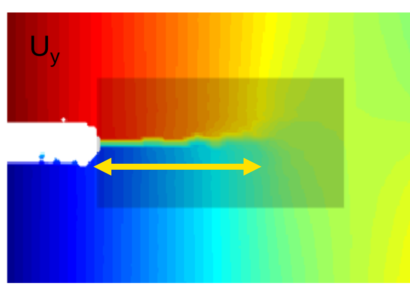
- Different measurement techniques
- vel gradient)
- ity disp. field)
- ng crack)
- and in-situ)
- techniques
- dence
- que



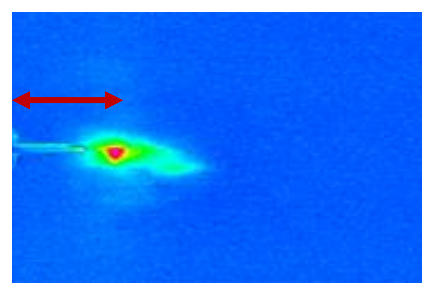




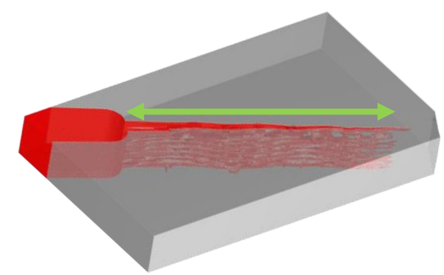
DIC tracking



IR Thermography



X-ray Tomography



[Pack 17]
[Panin 17]

[Lopez-Crespo 08]
[Vanlanduit 09]
[Catalanotti 10]

[Muller 16]
[Archer 17]

X-Ray tomography by Safran Aircraft Engines

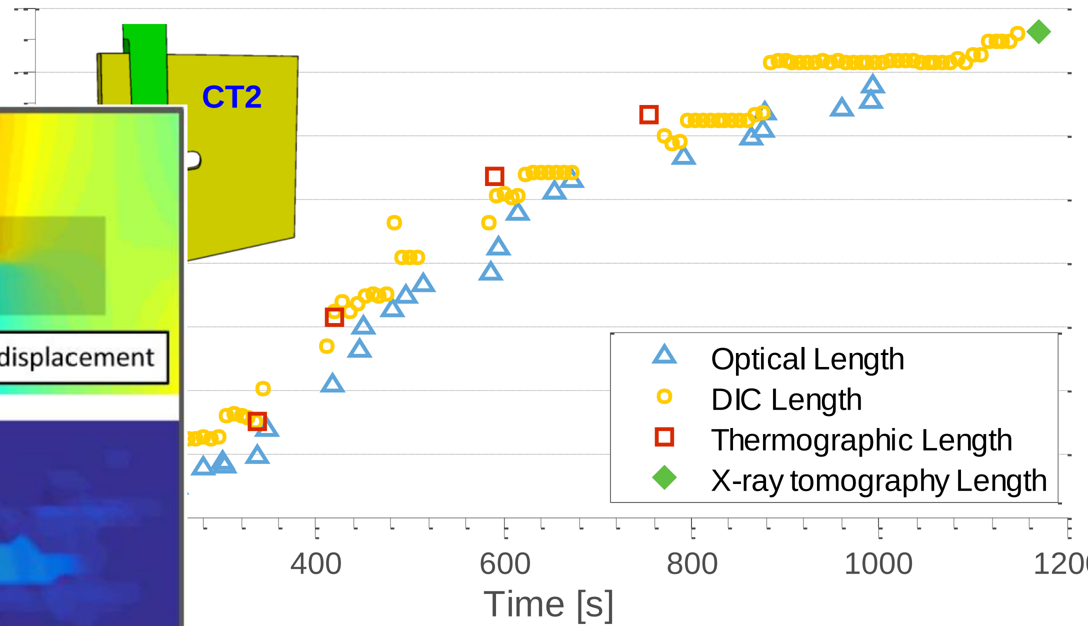
Measurement of macroscopic crack propagation

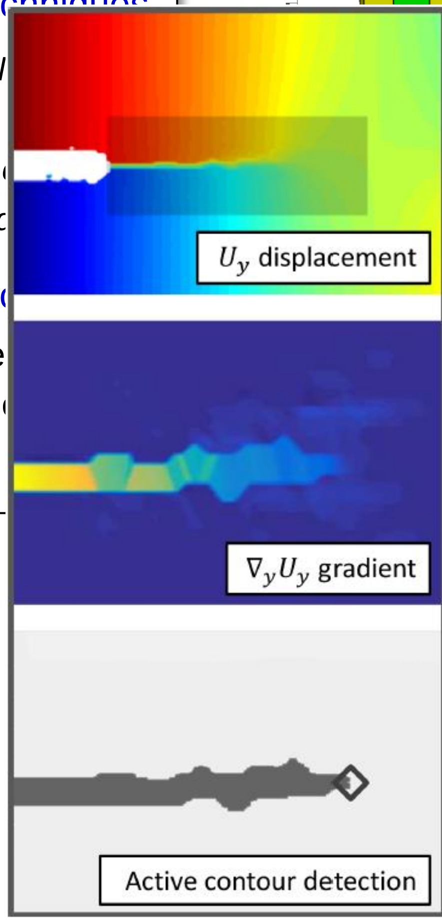
Mod. Test Sim.

Crack propagation

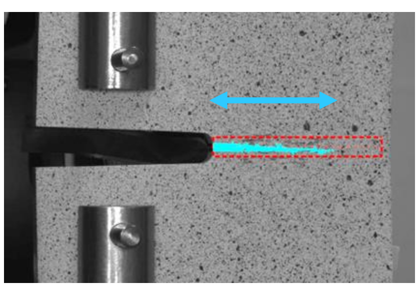
- Different measurement techniques
  - Optical tracking *(grey level*
  - DIC tracking *(discontinuity*
  - IR thermography *(heating*
  - X-Ray tomography *(ex and*
- Different measurement te
  - Cross-check to ↗ confide
  - Complementary techniqu

    Surface, volume, …





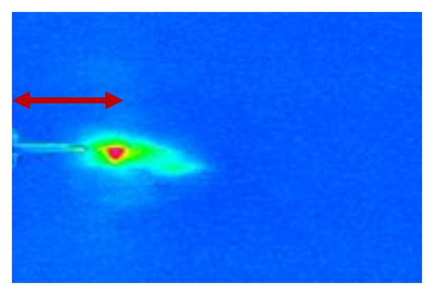
Optical tracking



[Pack 17]
[Panin 17]

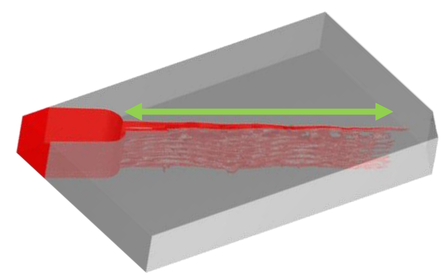
[Lopez-Crespo 08]
[Vanlanduit 09]
[Catalanotti 10]

IR Thermography



[Muller 16]
[Archer 17]

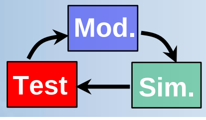
X-ray Tomography



X-Ray tomography by Safran Aircraft Engines

ONERA

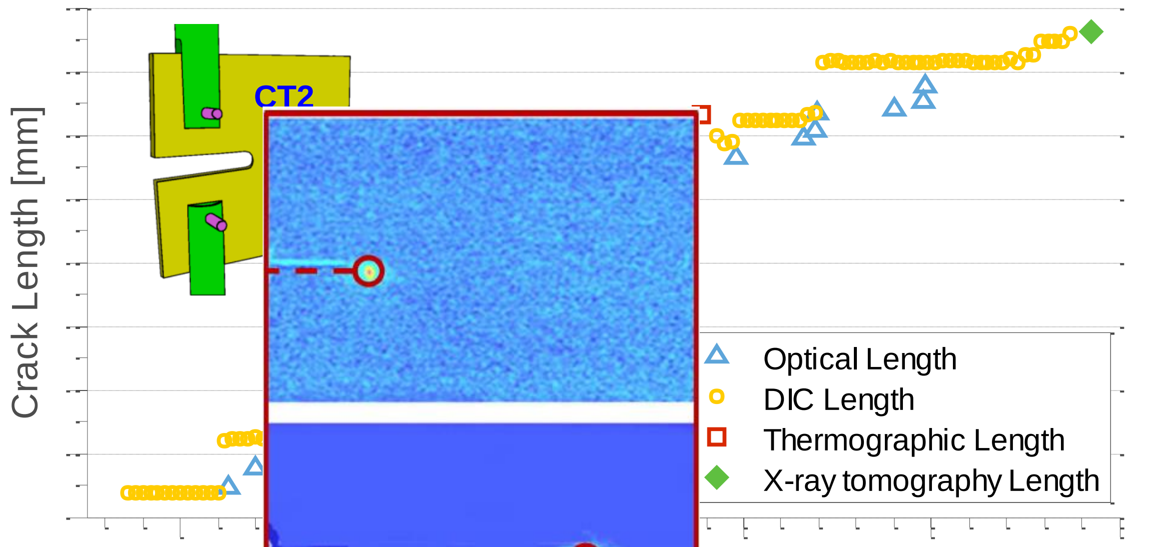
Measurement of macroscopic crack propagation

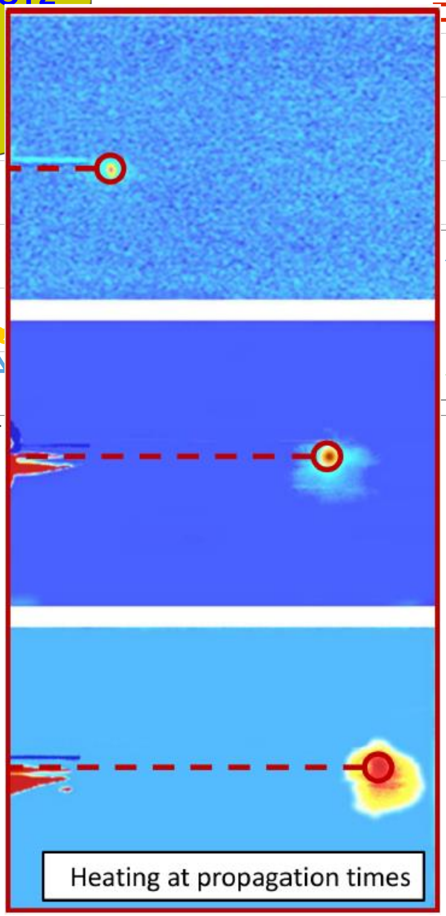


Crack propagation

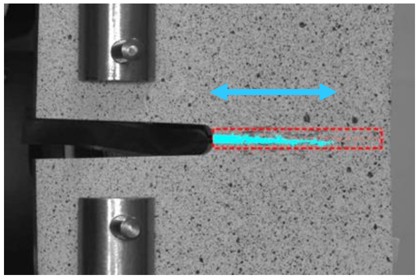
- Different measurement techniques
  - Optical tracking *(grey level gradient)*
  - DIC tracking *(discontinuity disp. field)*
  - IR thermography *(heating crack)*
  - X-Ray tomography *(ex and in-situ)*
- Different measurement techniques
  - Cross-check to ↗ confidence
  - Complementary technique

    Surface, volume, …



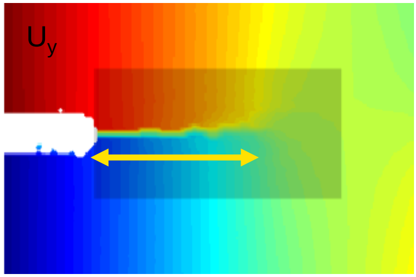


Optical tracking



[Pack 17]
[Panin 17]

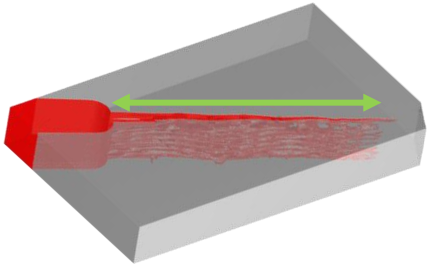
DIC tracking



[Lopez-Crespo 08]
[Vanlanduit 09]
[Catalanotti 10]

[Muller 16]
[Archer 17]

X-ray Tomography



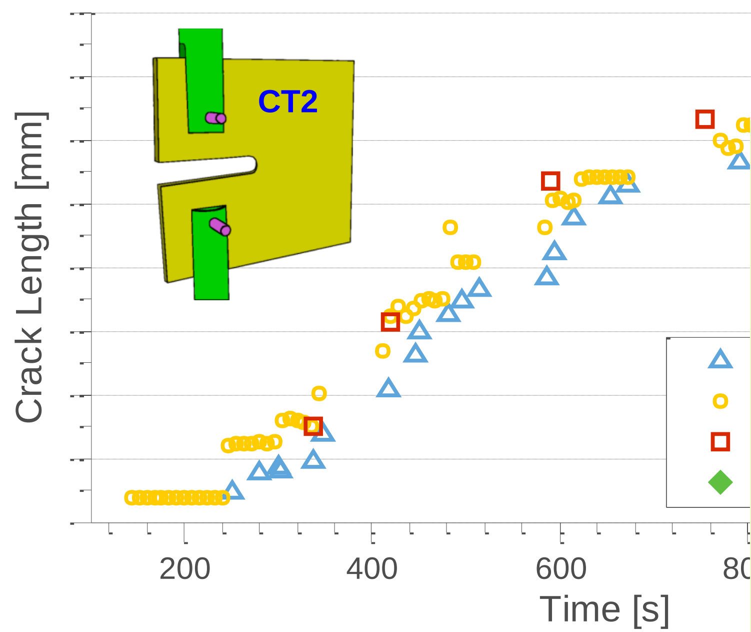
X-Ray tomography by Safran Aircraft Engines

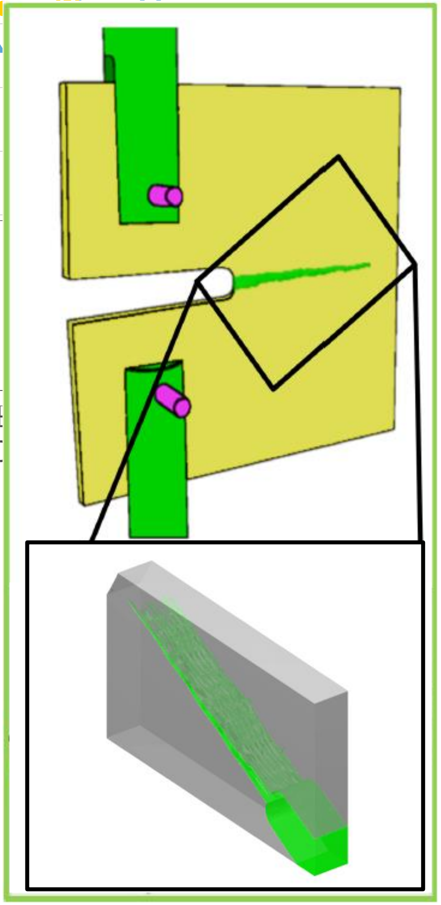
Measurement of macroscopic crack propagation

Crack propagation

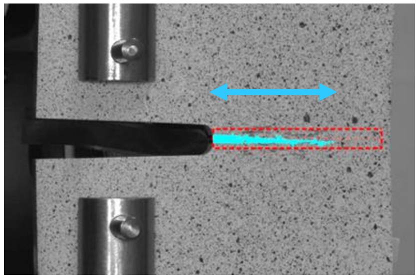
- Different measurement techniques
  - Optical tracking *(grey level gradient)*
  - DIC tracking *(discontinuity disp. field)*
  - IR thermography *(heating crack)*
  - X-Ray tomography *(ex and in-situ)*
- Different measurement techniques
  - Cross-check to ↗ confidence
  - Complementary technique

    Surface, volume, …

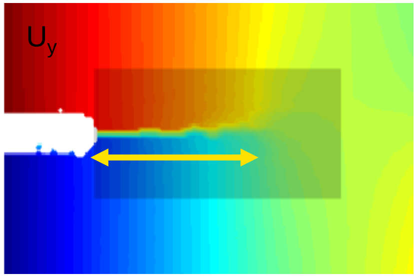




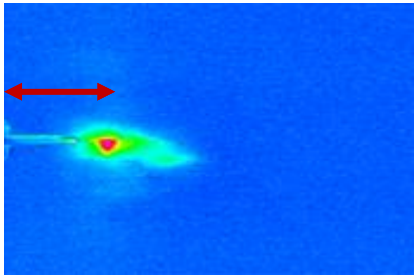
Optical tracking



DIC tracking



IR Thermography



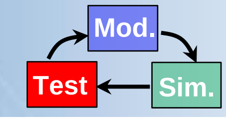
[Pack 17]
[Panin 17]

[Lopez-Crespo 08]
[Vanlanduit 09]
[Catalanotti 10]

[Muller 16]
[Archer 17]

X-Ray tomography by Safran Aircraft Engines

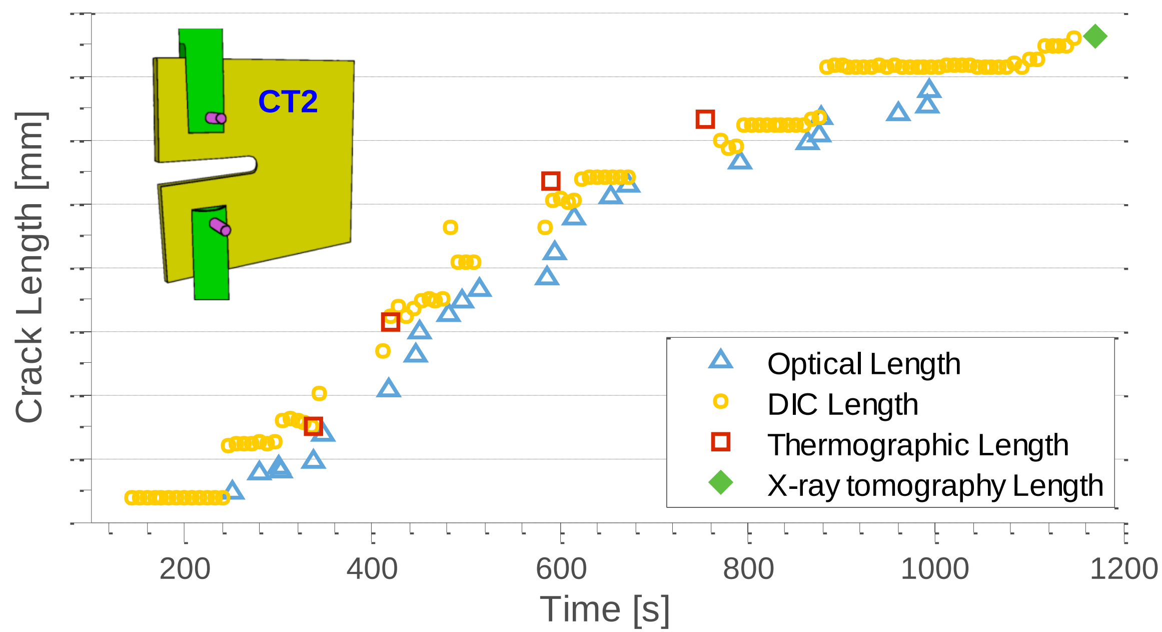
Measurement of macroscopic crack propagation



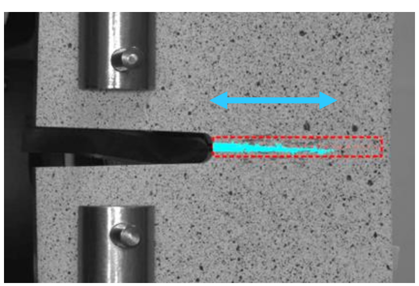
Crack propagation

- Different measurement techniques
  - Optical tracking *(grey level gradient)*
  - DIC tracking *(discontinuity disp. field)*
  - IR thermography *(heating crack)*
  - X-Ray tomography *(ex and in-situ)*
- Different measurement techniques
  - Cross-check to ↗ confidence
  - Complementary technique

    Surface, volume, …

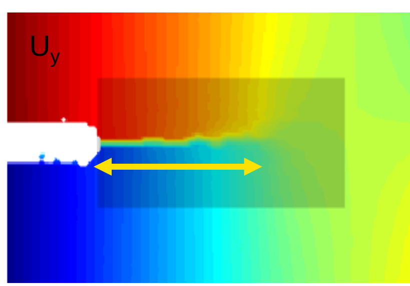


Optical tracking



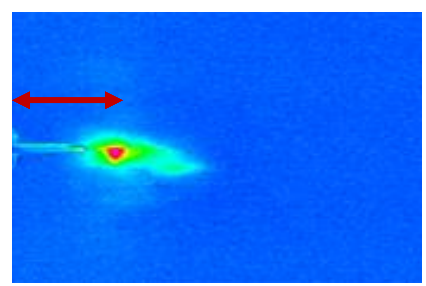
📖 *[Pack 17]*
[Panin 17]

DIC tracking



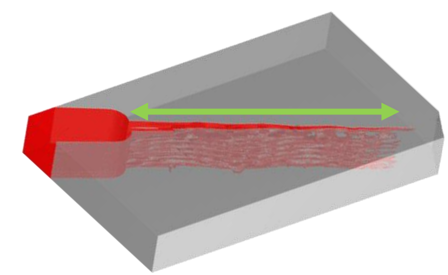
📖 *[Lopez-Crespo 08]*
[Vanlanduit 09]
[Catalanotti 10]

IR Thermography



📖 *[Muller 16]*
[Archer 17]

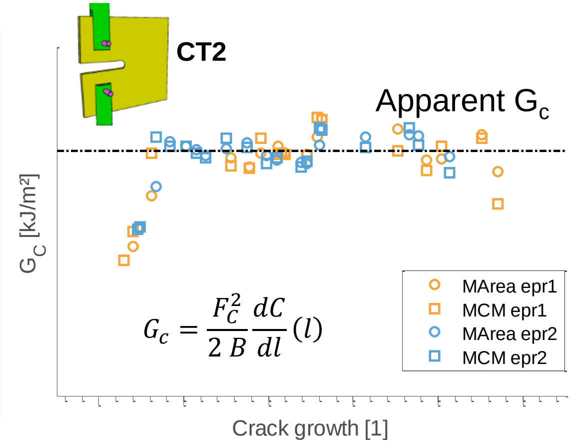
X-ray Tomography

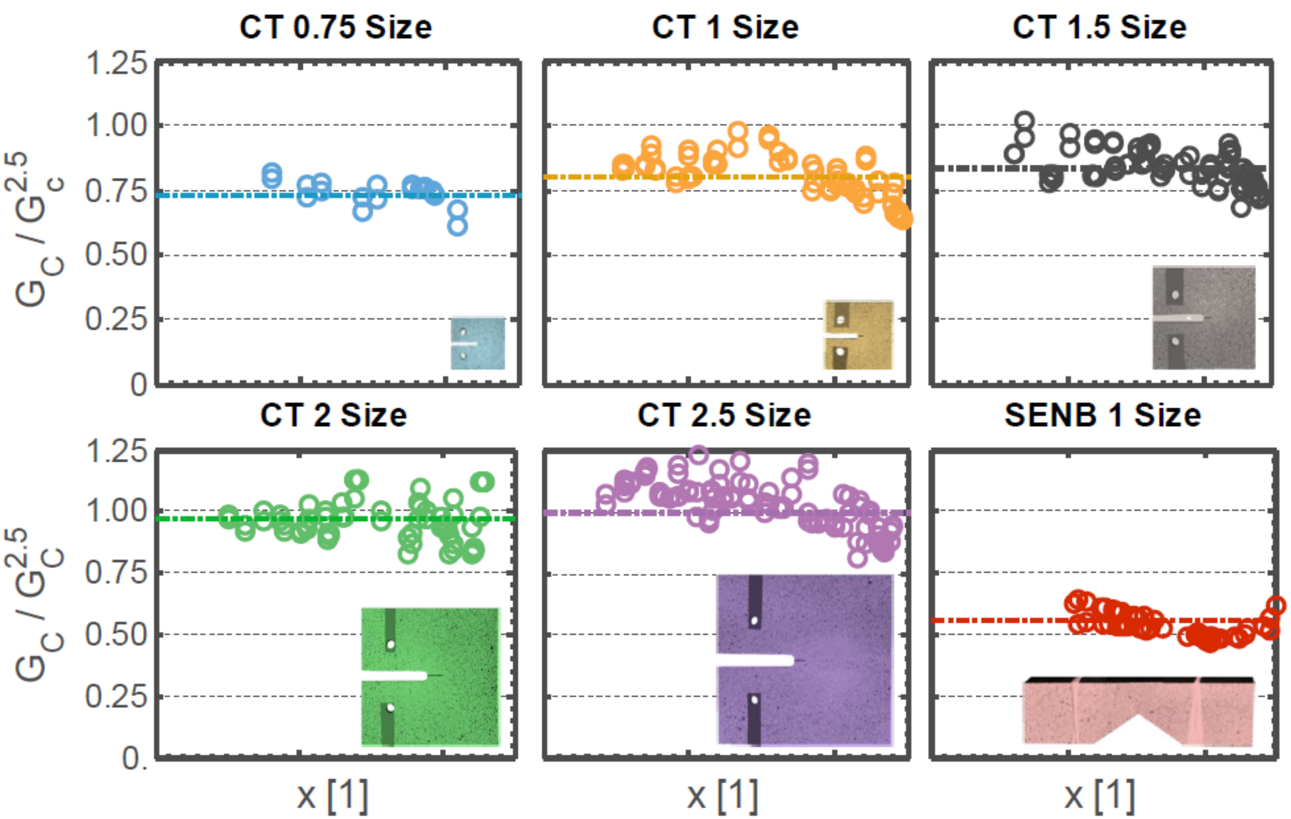


X-Ray tomography by
Safran Aircraft Engines

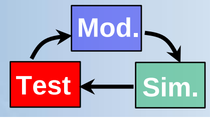
Analysis of the available tests

- G_C estimation for different sizes and types of specimens
  - Estimation with *Area Method* and the *Modified Compliance Method*
  - Evolution of apparent G_c as a function of the size of CT specimen
  - Different G_c for different types of specimens (CT and SENB)
- Use of LEFM is not relevant for 3D woven composites



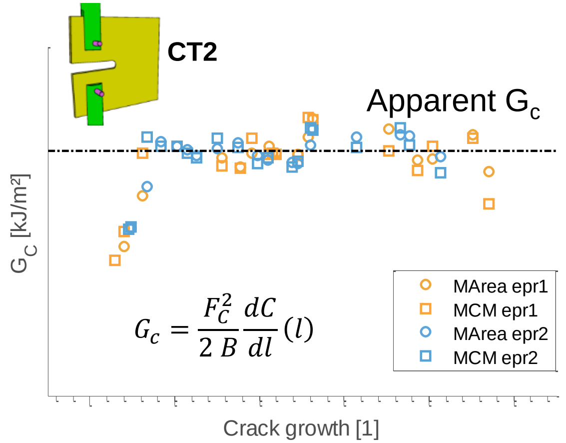


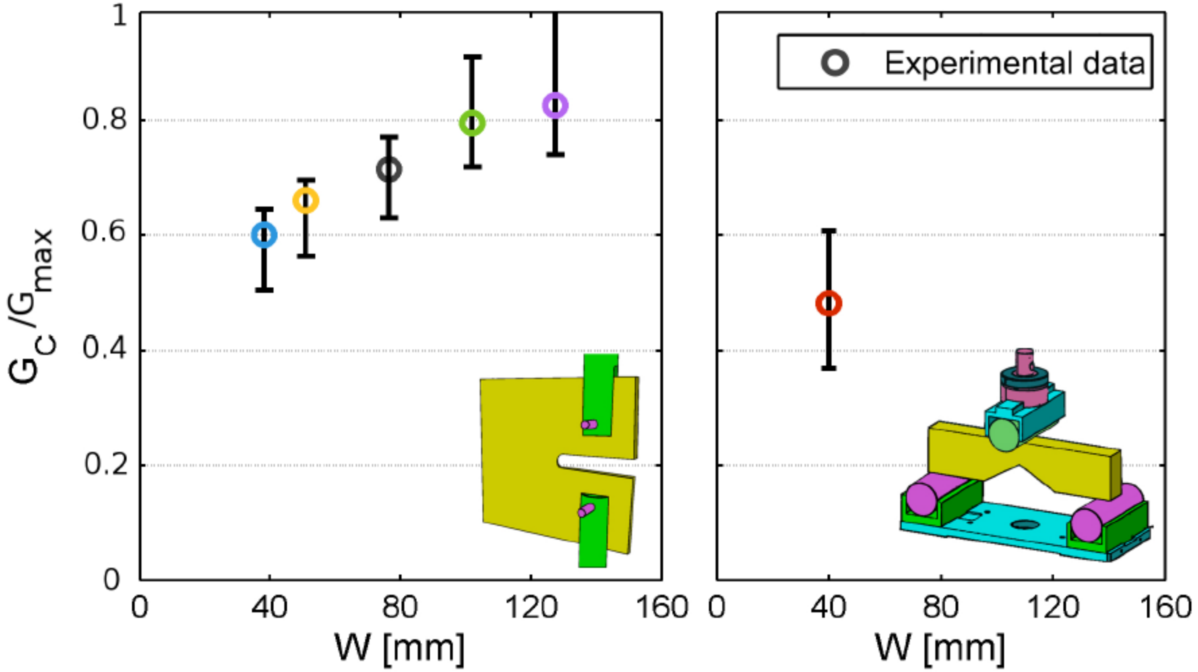
[Medeau 17]



Analysis of the available tests

- G_C estimation for different sizes and types of specimens
  - Estimation with *Area Method* and the *Modified Compliance Method*
  - Evolution of apparent G_c as a function of the size of CT specimen
  - Different G_c for different types of specimens (CT and SENB)
- Use of LEFM is not relevant for 3D woven composites



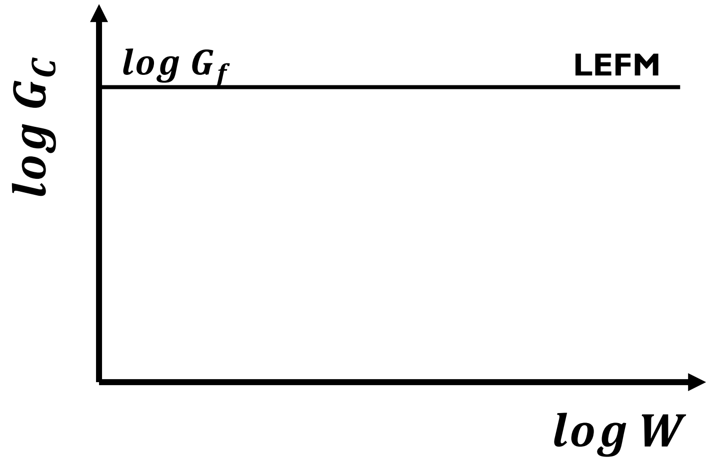


[Medeau 17]

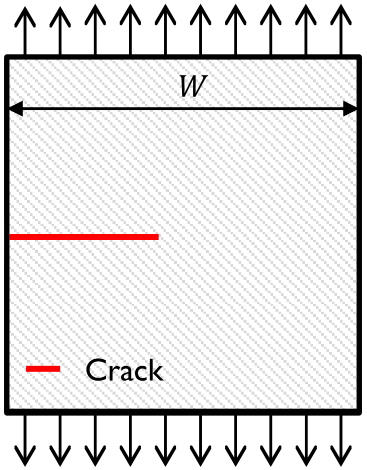
Scaling laws

- Scaling laws (different sizes W) for materials without internal lengths [Bazant 93]
  - With linear fracture mechanism: $\sigma_C \propto 1/\sqrt{W}$, $G_c \propto 1$ and $F_R \propto \sqrt{W}$
  - With stress based model: $\sigma_C \propto 1,$ $G_c \propto W$ and $F_R \propto W$
- Scaling laws for materials with internal lengths
  - Already available for concrete and rock [Bazant 84, 93]
  - Introduction of internal length c_f linked to microstructure:
    - G_f : asymptotic energy release rate when $W \gg c_f$
    - W_0 : transition length depends on c_f and specimen geometry

$$G_c = \frac{G_f}{1 + \frac{W_0(c_f)}{W}}$$



Transition between LFEM/ stress model

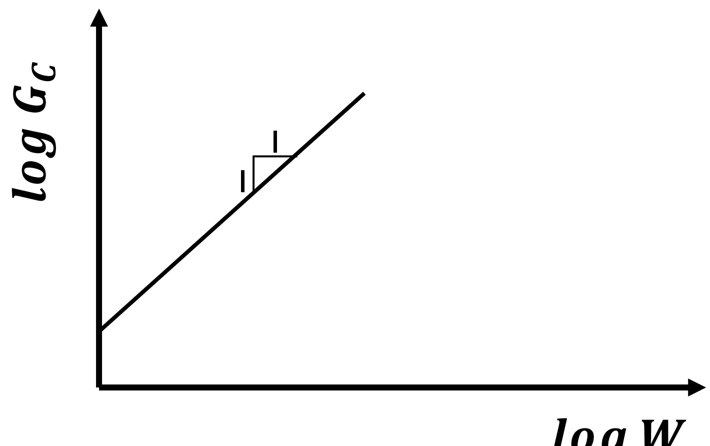


LEFM Crack

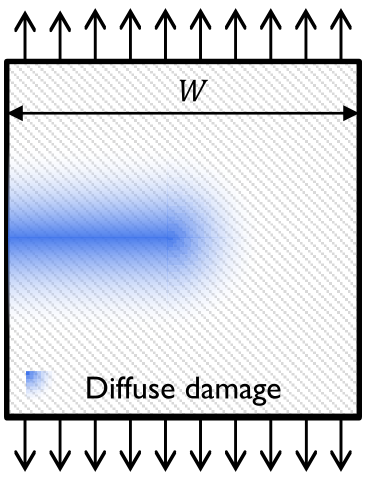
Scaling laws

- Scaling laws (different sizes W) for materials without internal lengths [Bazant 93]
  - With linear fracture mechanism: $\sigma_C \propto 1/\sqrt{W}$, $G_c \propto 1$ and $F_R \propto \sqrt{W}$
  - With stress based model: $\sigma_C \propto 1,$ $G_c \propto W$ and $F_R \propto W$
- Scaling laws for materials with internal lengths
  - Already available for concrete and rock [Bazant 84, 93]
  - Introduction of internal length c_f linked to microstructure:
    - G_f : asymptotic energy release rate when $W \gg c_f$
    - W_0 : transition length depends on c_f and specimen geometry

$$G_c = \frac{G_f}{1 + \dfrac{W_0(c_f)}{W}}$$



Transition between LFEM/ stress model

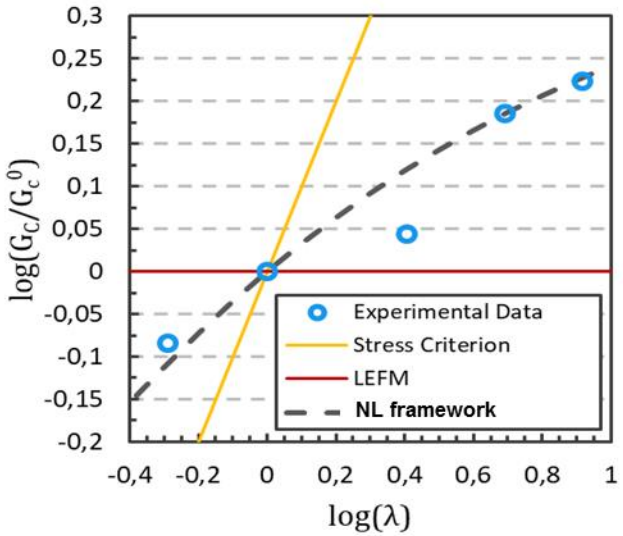


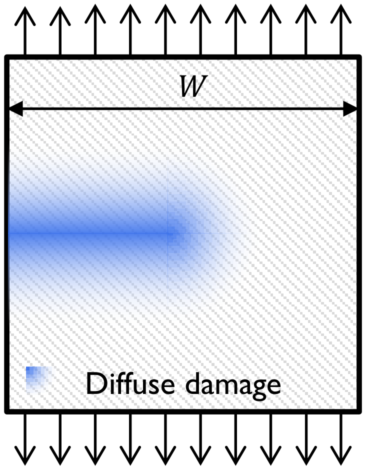
Stress based model

Scaling laws

- Scaling laws (different sizes W) for materials without internal lengths *[Bazant 93]*
  - With linear fracture mechanism: $\sigma_C \propto 1/\sqrt{W}$, $G_c \propto 1$ and $F_R \propto \sqrt{W}$
  - With stress based model: $\sigma_C \propto 1$, $G_c \propto W$ and $F_R \propto W$
- Scaling laws for materials with internal lengths
  - Already available for concrete and rock *[Bazant 84, 93]*
  - Introduction of internal length c_f linked to microstructure:
    - G_f : asymptotic energy release rate when $W \gg c_f$
    - W_0 : transition length depends on c_f and specimen geometry

$$G_c = \frac{G_f}{1 + \frac{W_0(c_f)}{W}}$$

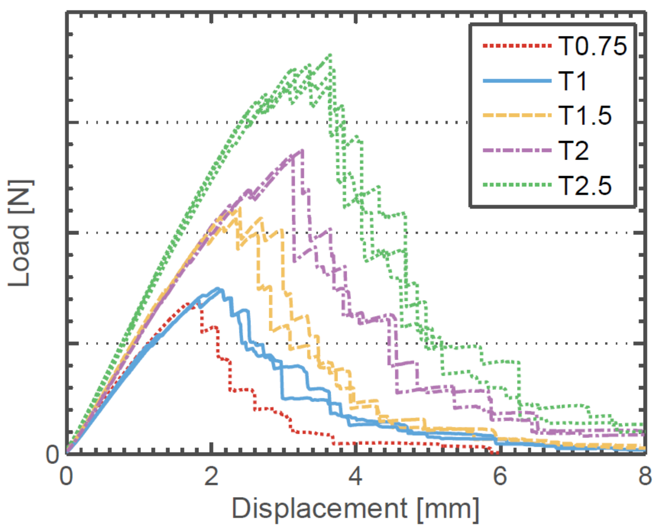


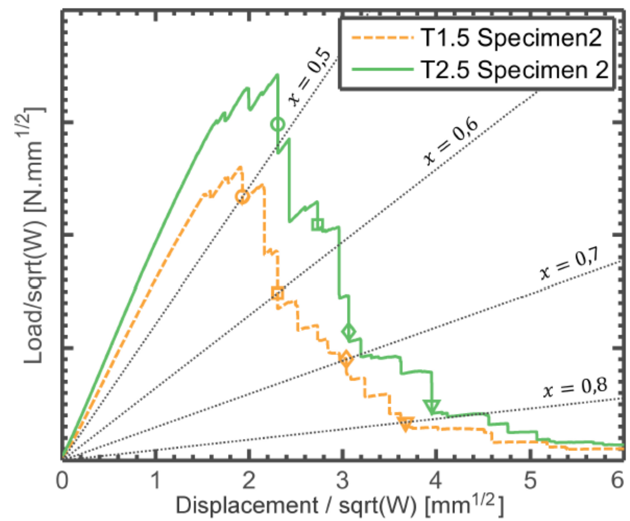


Scaling laws

- Scaling laws (different sizes W) for materials without internal lengths [Bazant 93]
  - With linear fracture mechanism: $\sigma_C \propto 1/\sqrt{W}$, $G_c \propto 1$ and $F_R \propto \sqrt{W}$
  - With stress based model: $\sigma_C \propto 1,$ $G_c \propto W$ and $F_R \propto W$
- Scaling laws for materials with internal lengths
  - Already available for concrete and rock [Bazant 84, 93]
  - Introduction of internal length c_f linked to microstructure:
    - G_f : asymptotic energy release rate when $W \gg c_f$
    - W_0 : transition length depends on c_f and specimen geometry

$$G_c = \frac{G_f}{1 + \frac{W_0(c_f)}{W}}$$



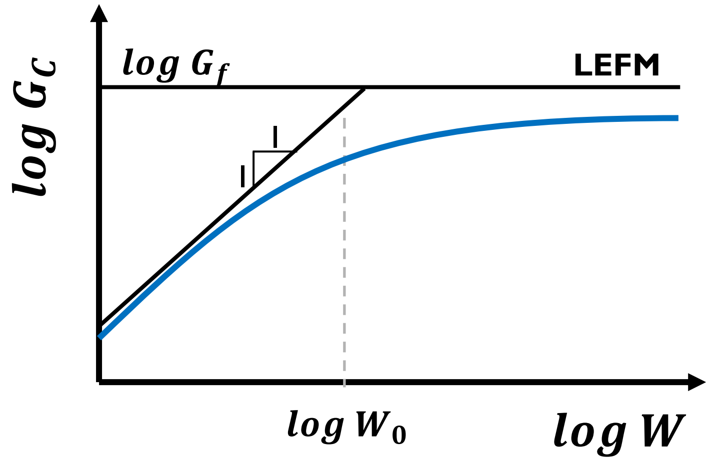


ONERA

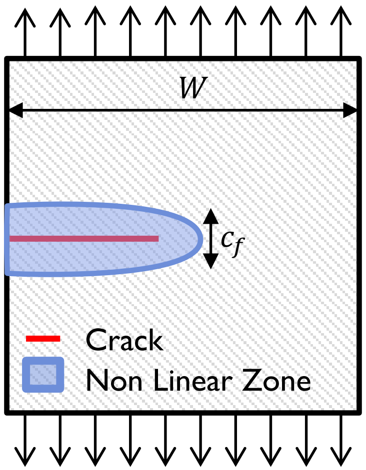
Scaling laws

- Scaling laws (different sizes W) for materials without internal lengths *[Bazant 93]*
  - With linear fracture mechanism: $\sigma_C \propto 1/\sqrt{W}$, $G_c \propto 1$ and $F_R \propto \sqrt{W}$
  - With stress based model: $\sigma_C \propto 1$, $G_c \propto W$ and $F_R \propto W$
- Scaling laws for materials with internal lengths
  - Already available for concrete and rock *[Bazant 84, 93]*
  - Introduction of internal length c_f linked to microstructure:
    - G_f : asymptotic energy release rate when $W \gg c_f$
    - W_0 : transition length depends on c_f and specimen geometry

$$G_c = \frac{G_f}{1 + \frac{W_0(c_f)}{W}}$$



Apparent G_c evolution with NLFM



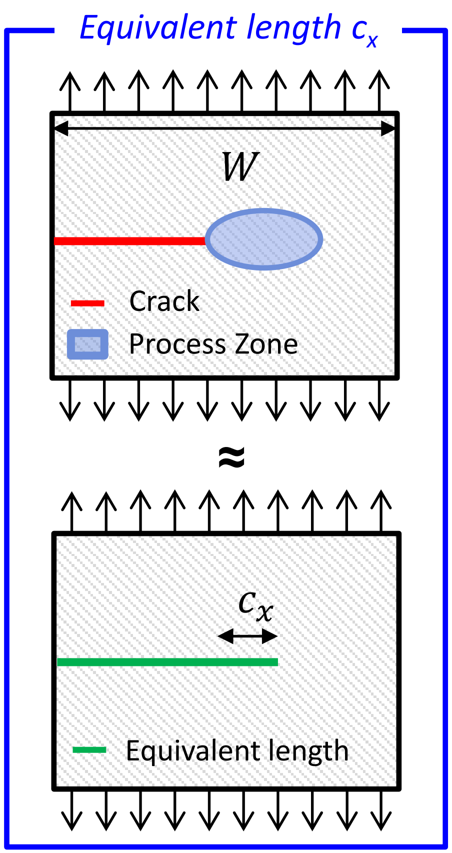
Non linear elastic cracking area

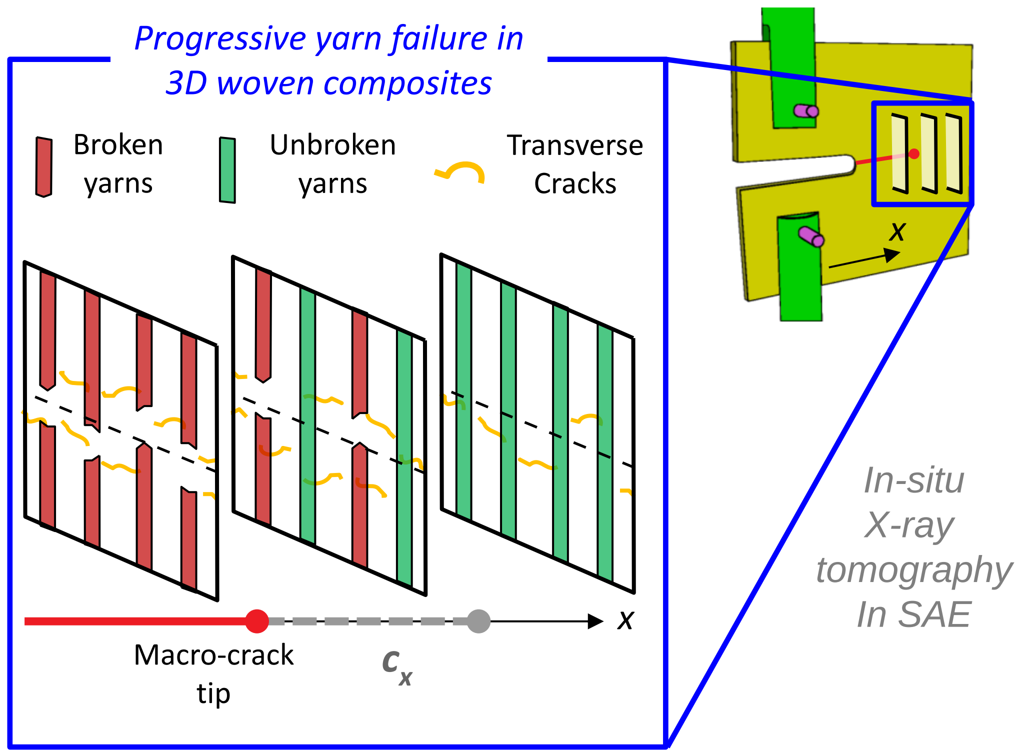
Experimental study on internal lengths (1/2)

Internal lengths in 3D woven composites (1/2)

Internal length along the crack path c_x

- Progressive yarn cracking along the crack path highlighted using in-situ μ-tomography
- Phenomenon guided by the architecture: linked to the inter-yarn length



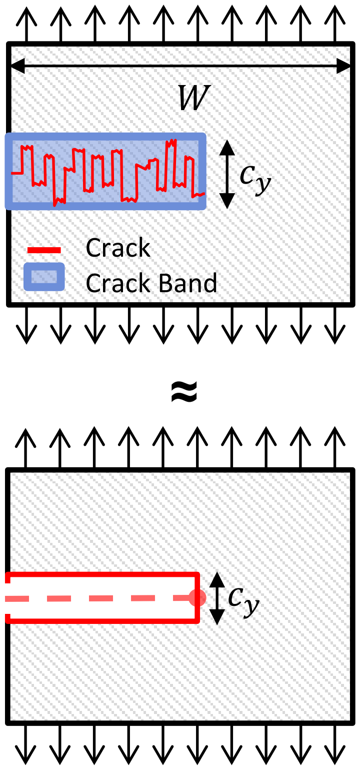


Experimental study on internal lengths (2/2)

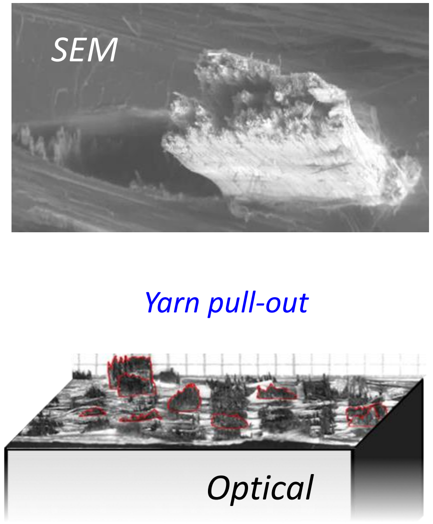
Internal lengths in 3D woven composites (2/2)

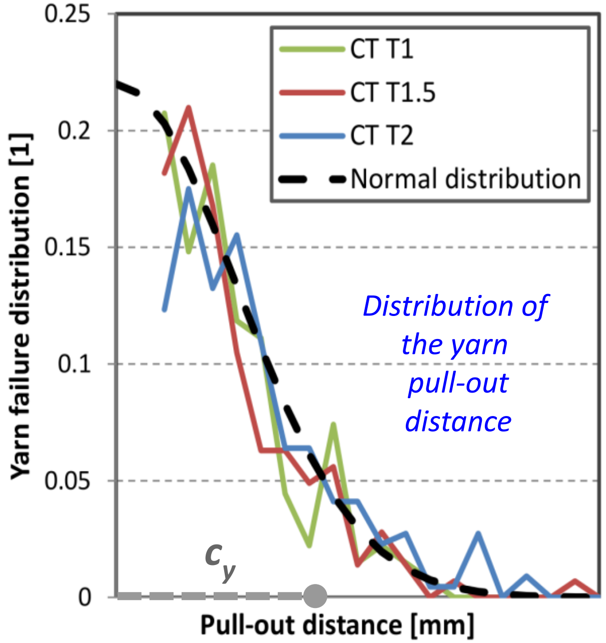
- Internal length along the crack path c_y
  - SEM and macro-pictures of the fracture profile exhibit a distribution of the yarn cracking length, associated with pull-out.
  - Measured on CT with different sizes: no variation with the specimen size

Equivalent length c_y

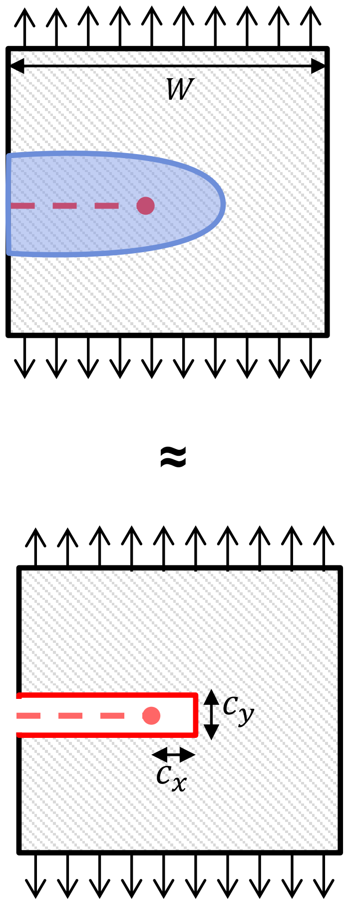


Experimental study on yarn pull-out





Real configuration



Equivalent LE configuration

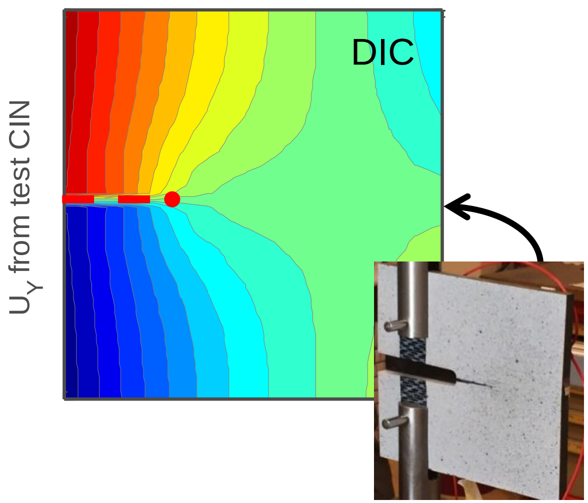
Non-linear framework

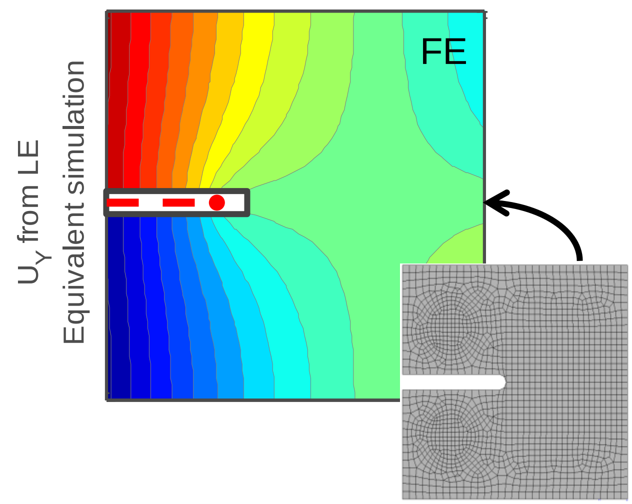
- LE equivalent configuration: Far field approximation
  - Determination of an equivalent configuration (c_x, c_y) providing the same effects away from the crack
- Determination of the critical energy release rate

$$G_c = \frac{F_C^2}{W}\, g\left(\frac{a}{W}+\frac{c_x}{W},\frac{c_y}{W}\right) \cong \frac{G_f}{1+\frac{\partial_x g(x)\, c_x}{g(x)W}+\frac{\partial_y g(x)\, c_y}{g(x)W}} \leftrightarrow \frac{G_f}{1+\frac{W_0}{W}}$$

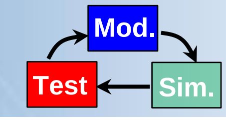
- 3 material parameters to be identified (G_f, c_x, c_y)
- A priori known parameters $(W, g(x), \partial_x g(x), \partial_y g(x))$

  $g(x)$ can be determined using linear elastic FE simulations



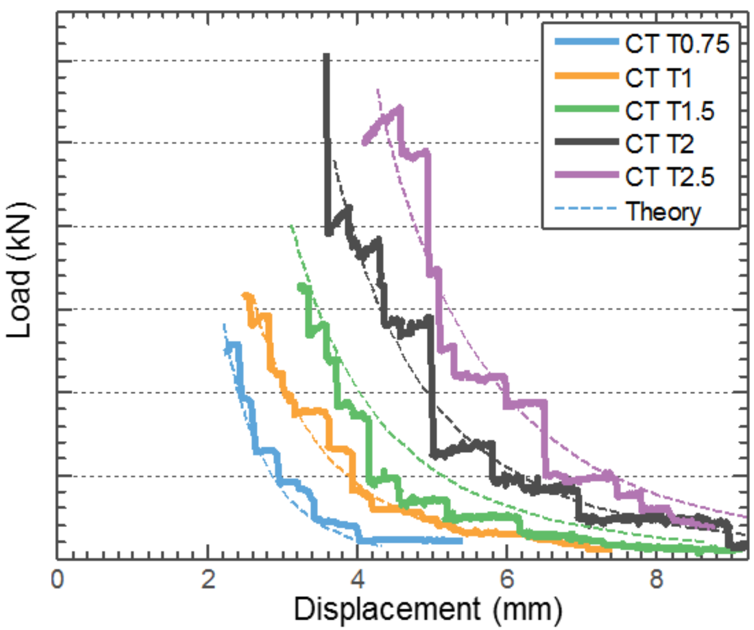


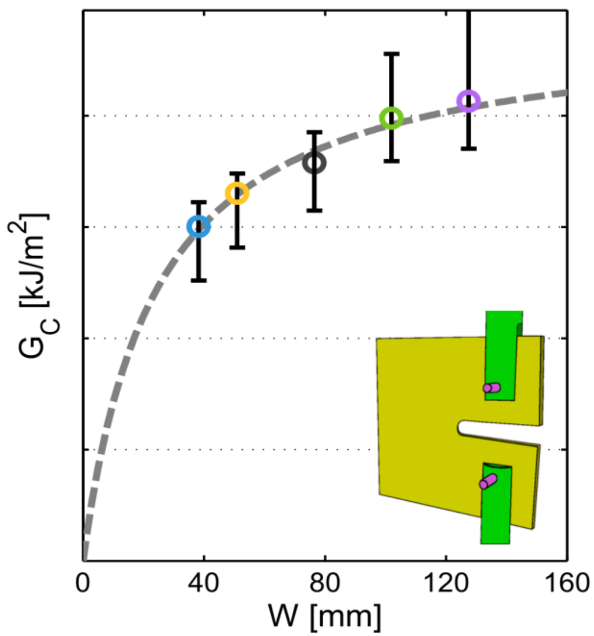
Identification and validation on test results

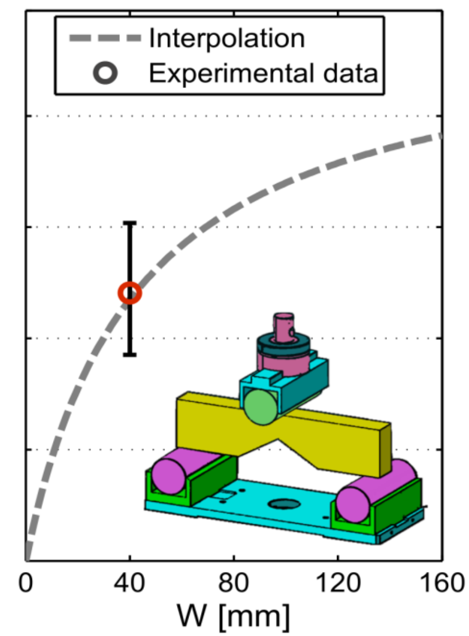


Validation of the proposed approach

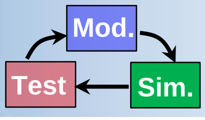
- **Identification protocol**
  - Determination through apparent G_c analysis of different tests (CT and SENB) of asymptotic critical energy release rate G_f and (c_x,c_y) strongly linked to the microstructure
- **Validation of the proposed non-linear framework**
  - Consistent evolution of the apparent $\boldsymbol{G_c}$ for different CT sizes
  - Consistent prediction of the apparent $\boldsymbol{G_c}$ for different types of tests
  - Good prediction of the load/displacement curves





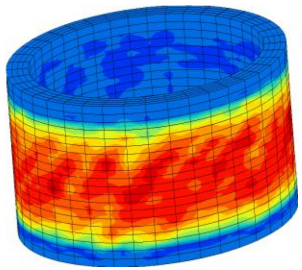


Strength prediction of large composite structures

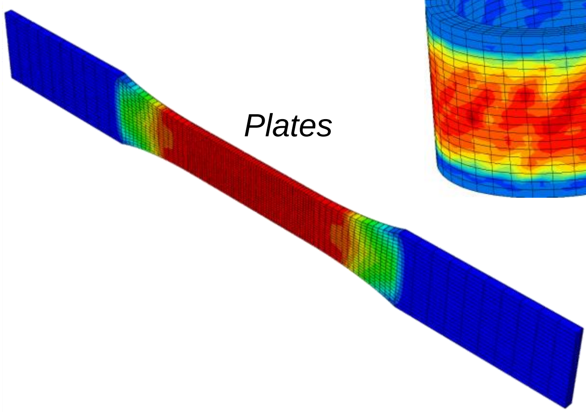


Elementary coupon scale

Tubes

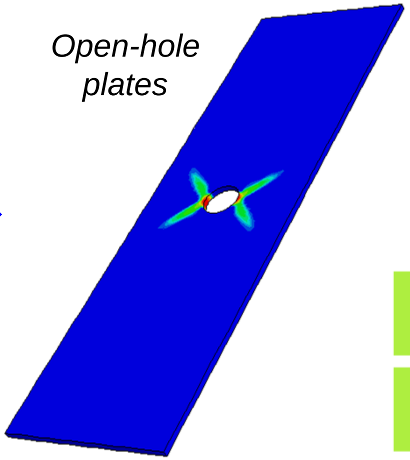


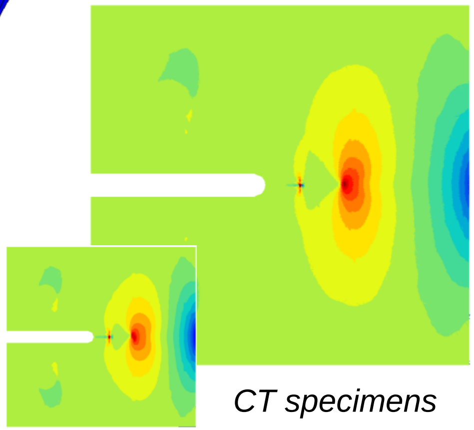
Plates



Composite structure scale

Open-hole plates

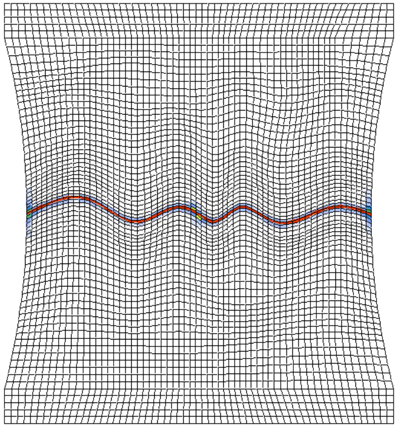




CT specimens

Implementation in FE codes

- Robust implementation in finite element codes
  - Implementation in a FE code with an implicit solver Zebulon
  - Softening behaviour after fibre yarn failure
  - Avoid mesh dependence problem (size and orientation of elements)
- Physically based regularization techniques
  - Regularisation methods to avoid localisation problem
  - Methods used in physical key quantities



Mesh dependency problem

ONERA

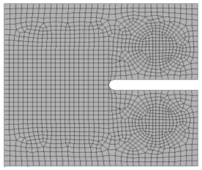
Presentation of the numerical test campaign

Models considered in the numerical test campaign

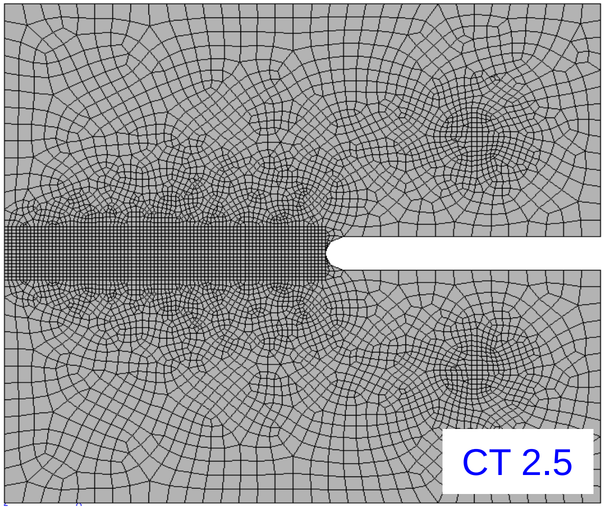
- Regularisation methods
  - Simulations performed with Z-set code in quasi-static
    - Delay effect methods *[Needleman 88], [Allix 97], [Suffis 03], [Berro 06]*
    - Non local approach *[Pijaudier-Cabot 87], [Peerlings 96], [Lorentz 05]*
    - Phase-field method *[Francfort Marigo 98], [Bourdin 00], [Miehe10]*
- Analysis of key quantities
  - Avoid localization problem/mesh dependence
  - Predictive scale effect on load/displacement curves and apparent G_c

Geometry and mesh

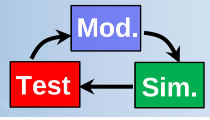
- Considered geometry
  - Simulations performed on CT specimens with different sizes from 0.5 to 2.5
- Considered meshes
  - Fixed element size along the crack path whatever the specimen size



CT 0.5



Material model with delay effect method



Delay effect methods

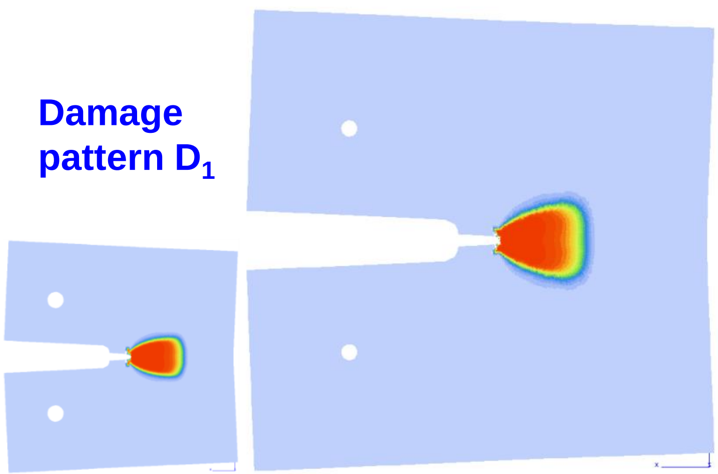
- **Principle of delay effect method**
  - *[Needleman 88], [Allix 97], [Suffis 03], [Allix 13]* *initially developed for dynamic problems*
  - *[Berro 06], [Marcin 10], [Hurmane 16]* *but also applied to quasi-static problems by other authors*
  - Introduction of a delay effect τ on damage
  - Avoid mesh dependence, easy to implement in FE code

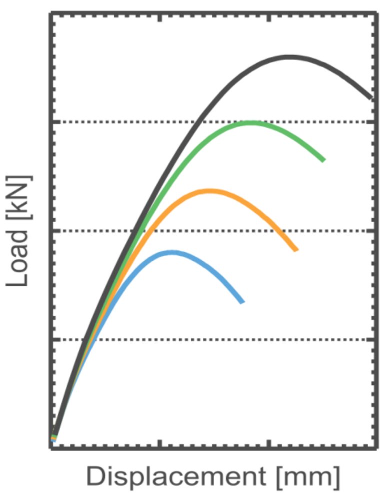
$$\boxed{\dot{D} = \frac{1}{\tau}\left(F(y) - D\right)}$$

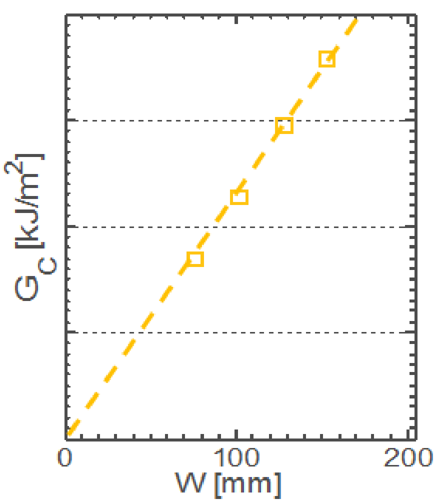
- **Scale effect predictions**
  - Evolution of failure load F_R as a function of W
  - Linear evolution of the apparent G_c
  - No internal length and energy control

→ **Delay effect provides inaccurate scale effect for 3D woven composites**

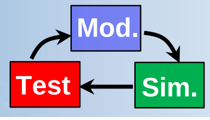
Damage pattern D_1







Material model with delay effect method



Delay effect methods

Principle of delay effect method

- *[Needleman 88], [Allix 97], [Suffis 03], [Allix 13]* *initially developed for dynamic problems*
- *[Berro 06], [Marcin 10], [Hurmane 16]* *but also applied to quasi-static problems by other authors*

- Introduction of a delay effect τ on damage
- Avoid mesh dependence, easy to implement in FE code

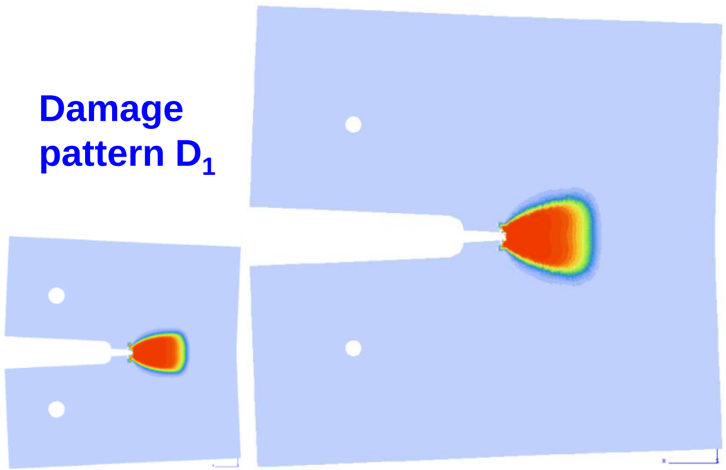
$$\boxed{\dot{D} = \frac{1}{\tau}\left(F(y) - D\right)}$$

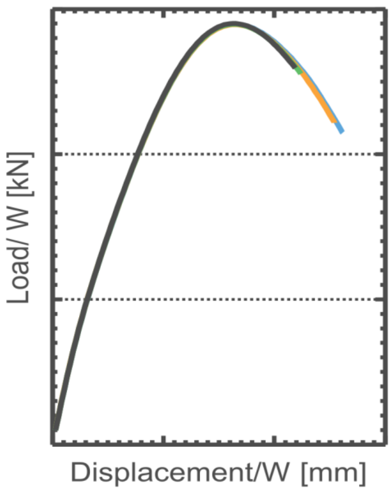
Scale effect predictions

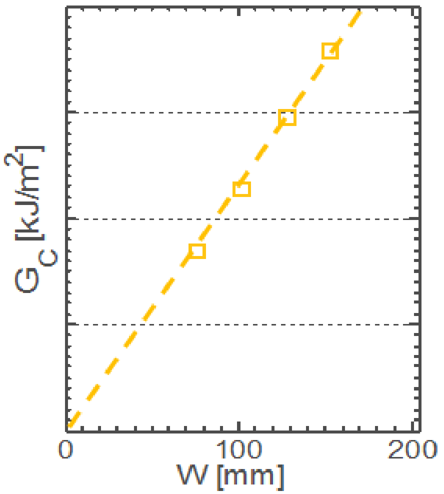
- Evolution of failure load F_R as a function of W
- Linear evolution of the apparent G_c
- No internal length and energy control

→ **Delay effect provides inaccurate scale effect for 3D woven composites**

Damage pattern D_1







ONERA

Material model with a non-local framework

Non-local approach

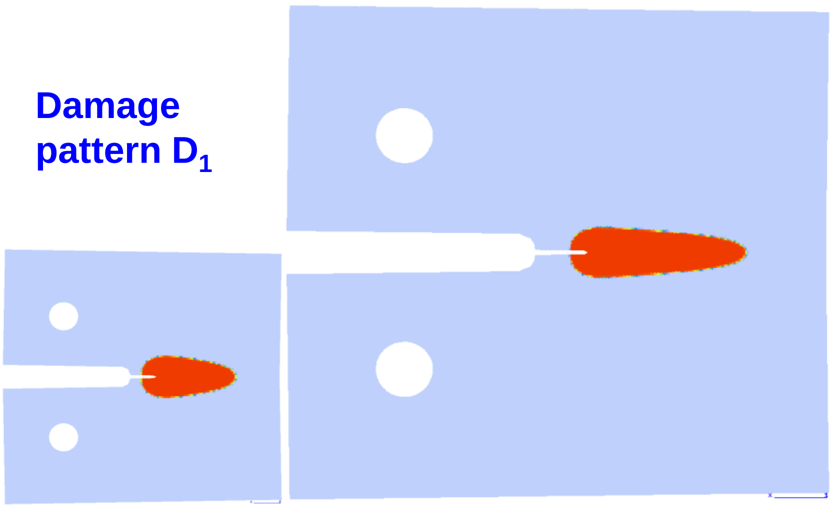
- Principle of non-local framework
  - *[Pijaudier-Cabot 87], [Peerlings 96], [Lorentz 05], [Germain 06]*
  - Diffused damage in a volume defined by an internal length l
  - Avoid mesh dependence, but **intrusive to FE code**

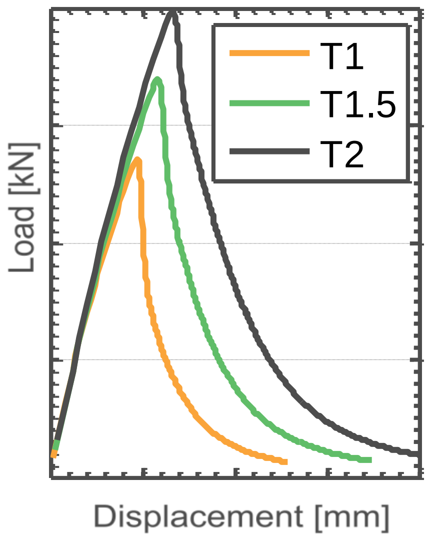
$$\boxed{\bar{Y} - l^2 \nabla^2 \bar{Y} = Y(\varepsilon)}$$

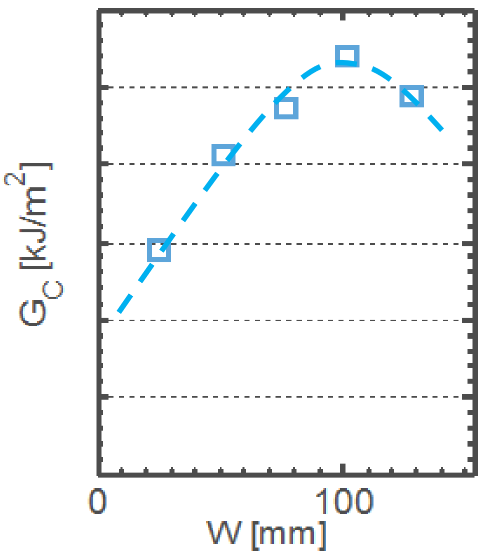
- Scale effect predictions
  - Complex evolution of failure load F_R and apparent G_c
  - Internal length considered but no energy control
  - No control of the crack failure pattern

→ **Non local qualitatively exhibits a relevant but complex scaling law**

Damage pattern D_1







Phase-field method

Principle of phase-field method

[Francfort Marigo 98], [Bourdin 00], [Miehe10]

- Diffused damage D with the introduction of (G_c, l)
- Intrusive to FE code but **numerical difficulties**

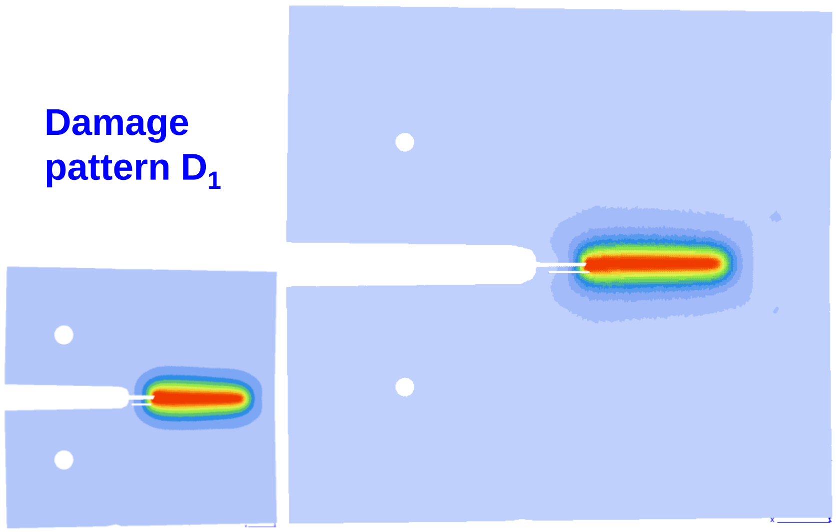
$$D - l^2\nabla^2 D = \frac{2l}{G_C}(1-D)E_0\varepsilon^2$$

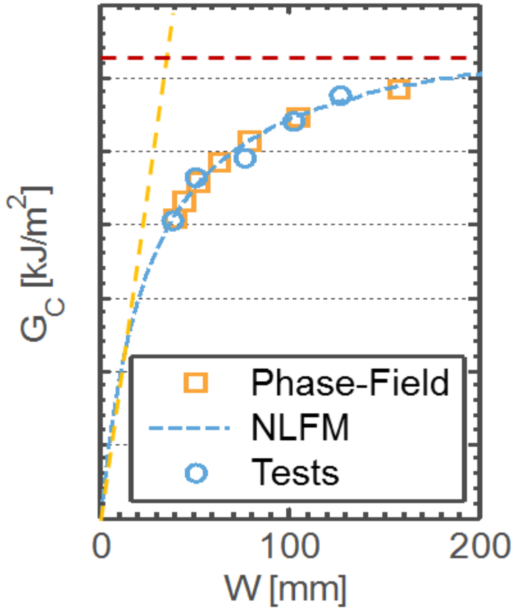
Scale effect predictions

- Accurate evolution of failure load F_R and apparent G_c
- Internal lengths l and energy control G_c
- Control of the crack failure pattern

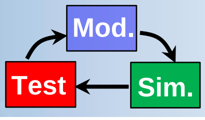
→ **Phase-field exhibits the accurate scaling law for 3D woven composites**

Damage pattern D_1





Material model with a phase-field method



Phase-field method

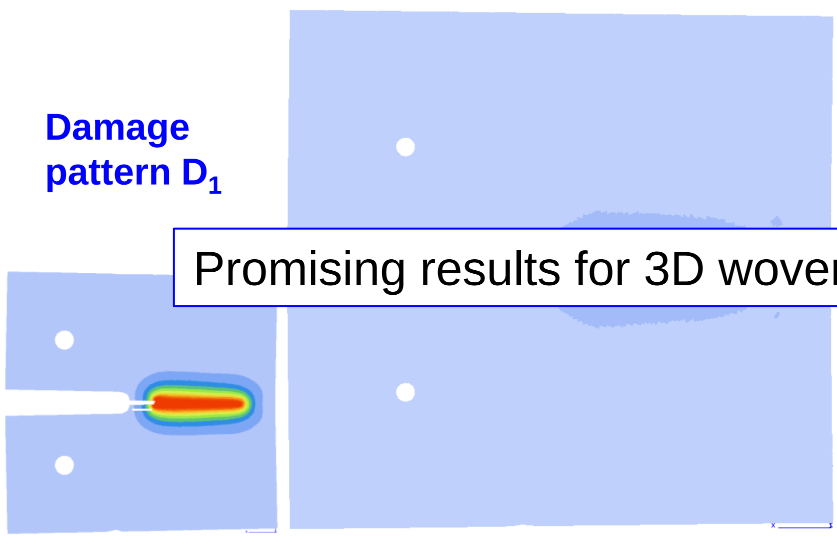
- Principle of phase-field method
  - *[Francfort Marigo 98], [Bourdin 00], [Miehe10]*
  - Diffused damage D with the introduction of (G_c, l)
  - Intrusive to FE code but **numerical difficulties**

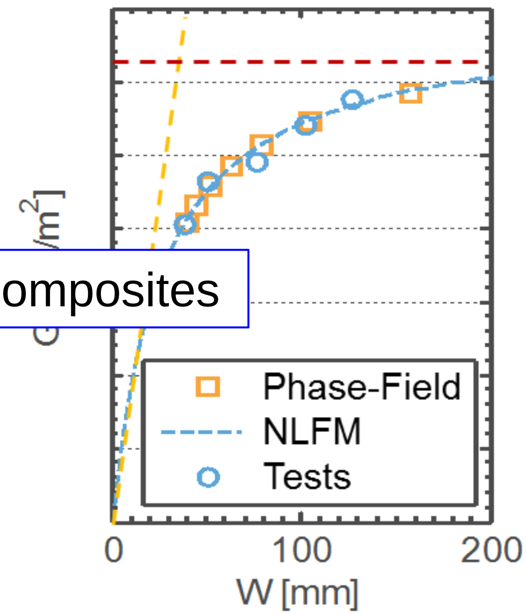
$$D - l^2 \nabla^2 D = \frac{2l}{G_C}(1 - D) E_0 \varepsilon^2$$

- Scale effect predictions
  - Accurate evolution of failure load F_R and apparent G_c
  - Internal lengths l and energy control G_c
  - Control of the crack failure pattern

→ **Phase-field exhibits the accurate scaling law for 3D woven composites**

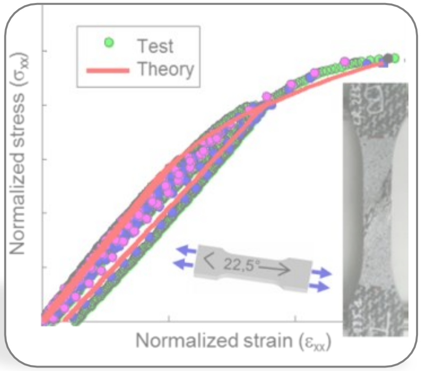
Damage pattern D_1





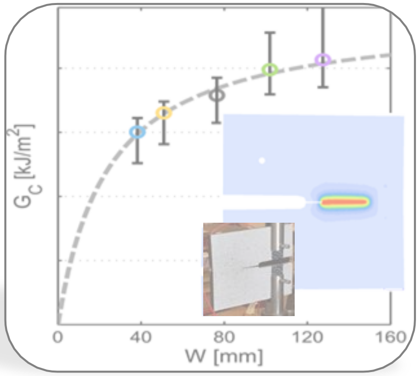
Promising results for 3D woven composites

Contents



Damage and failure model of elementary coupons

- Comprehension of the damage and failure mechanisms
- Proposition of a macroscopic damage and failure model
- Validation through comparisons with tests



Strength of composite structures with singularities

- Experimental study of progressive yarn failures
- Modelling of fibre yarn failure – physical key quantities
- Implementation of a softening behaviour in a FE code

Conclusions Perspectives	Advantages and limitations of failure approach Identification protocol – Validation tests

Conclusions / Perspectives

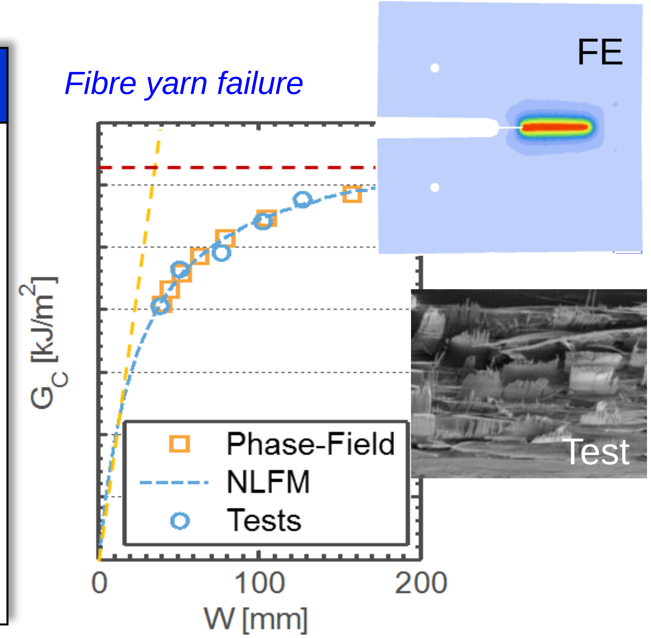
Conclusions

Damage mechanisms

- Diffuse damage oriented by microstructure in 3D woven composite
- Continuum damage model relevant for such a material
- Validation through comparisons with static/impact tests

Failure mechanisms

- Experimental study using CT and SENB tests
- Evolution of apparent G_c as a function of size and type of tests
- Non linear fracture framework relevant (energy + lengths)
- Phase-Field method promising for such a material



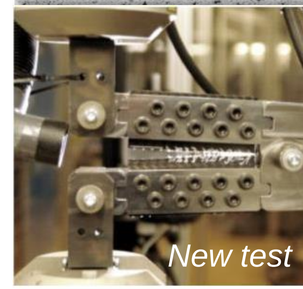
Perspectives

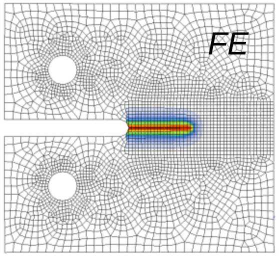
Experimental part

- Proposition of new configurations of test for validation
- Analysis tests with complex crack path (as in warp direction)
- Develop experimental device for CT tests in most reinforced direction

Numerical part

- Improve robustness of Phase-Field method in Zset code
- Application to other structures with different geometrical singularities





ONERA

THE FRENCH AEROSPACE LAB

return on innovation

www.onera.fr