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THE FRENCH AEROSPACE LAB

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Composite activities at ONERA

Composite material simulation with Europlexus

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Fundings:

Onera

Physafe II

Funded by the European Union
NextGenerationEU

Cleopatra

Presentation plan

- **Overview of ONERA activities**

- **Brief overview of composite materials modelling and recent development**

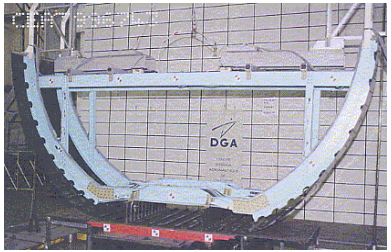
- **A workflow for composite materials modelling:**
  Chaining different finite element solver

Accidental dynamic loadings

Impact

Bird strike, ballistic limit/perforation

Crash fuselage



Sub-component impact

Assembly, with bearing

[Riccio et al, 2020]

Energy absorption system

Crush

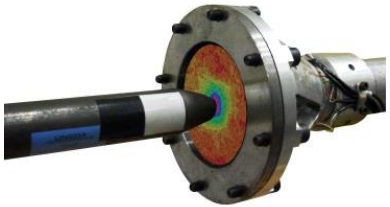
[Feraboli et al, 2016]

Ensure structural integrity and survivability for accidental loadings regarding certification requirements

Experimental devices at ONERA

Different load capacities and strain rate

Hopkinson bars, hydraulic jack, crash tower, airguns



Material characterisation for different strain rate

Propose specific test procedures for transient dynamic loading (no specific standards)

Validation tests

Gives information and validation test case for modelling

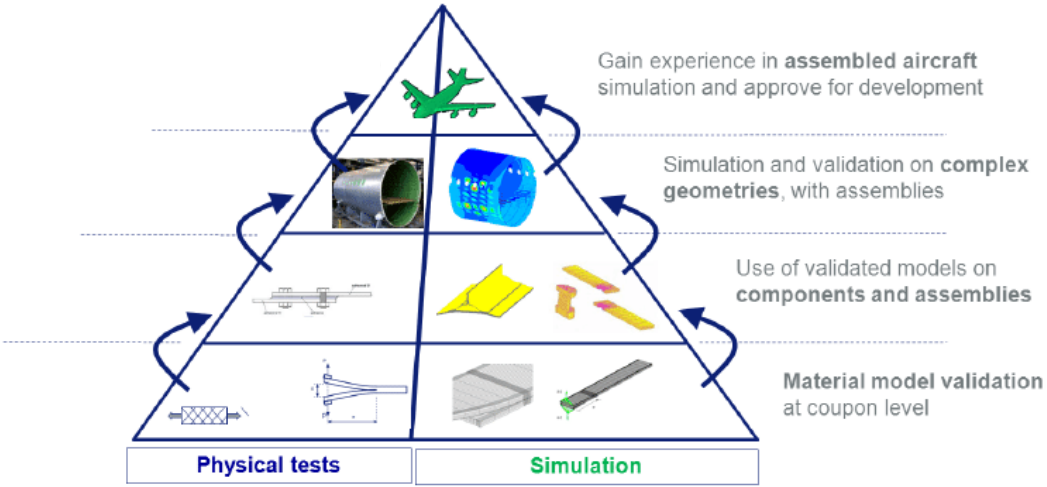
Test pyramid in the aerospace industry

From component level to the full structure

Elementary material characterisation

Test on sub-component (assembly, open-hole)

Structural scale for validation



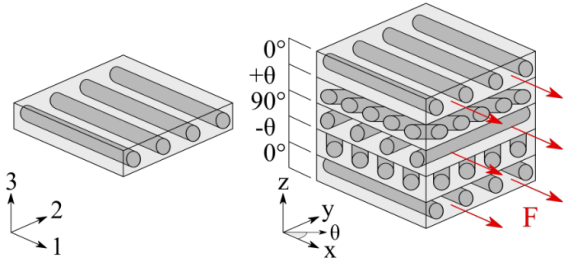
[Bruyneel et al, 2014]

Difficulty of modelling: Change of scale

Composite materials

Different architecture (UD, 2D, 3D…)

Laminated composites of unidirectionnal plies



Fuselage and wing panel [airbus.com]

Composite materials

Different architecture (UD, 2D, 3D…)

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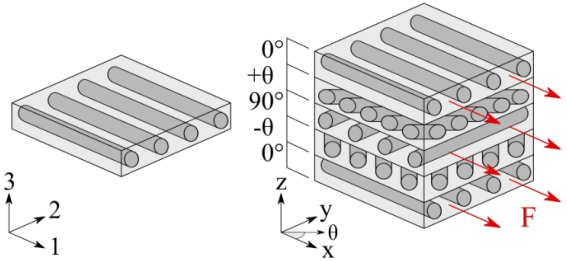
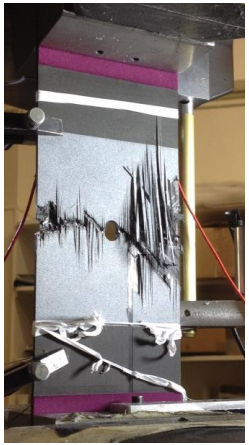
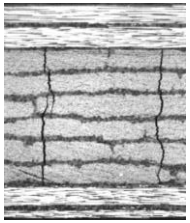


Fuselage and wing panel [airbus.com]

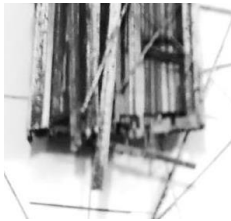
Damage mechanism





Transverse cracking

Delamination [Wisnom et al, 2009]



Fibre failure

Complex material behaviour (anisotropy, non-linear, rate sensitive)

Damage mechanism related to material architecture

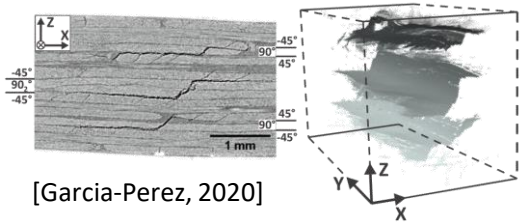
Weaknesses under out of plane loadings (delamination)

Interaction between damage mechanisms

Damage coupling: transverse cracking / delamination

Transverse cracking can trigger delamination

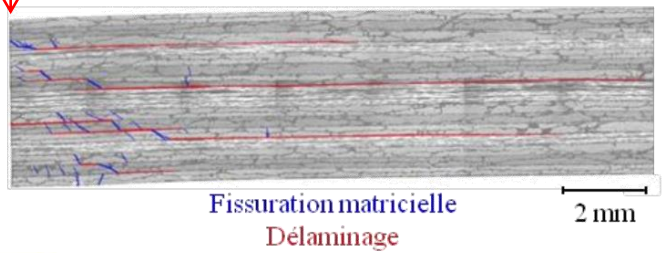
Out of plane shear → Transverse cracking → Delamination



[Garcia-Perez, 2020]

Impact location

[Trousset, 2013]



[Mortell et al, 2014]

Highly coupled damage mechanisms
complex phenomena that influence a structure strength or residual strength

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- **Overview of ONERA activities**

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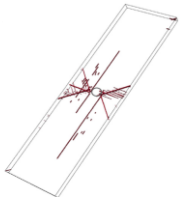
  Chaining different finite element solver

Composite material modelling

Ply modelling

Discrete damage models

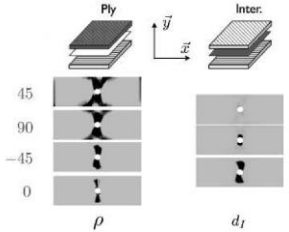
[Hallett et al, 2008]
[Bouvet et al, 2009]
[Van Der Meer et al, 2009]



Floating Nodes [Chen et al, 2016]

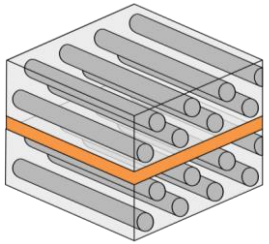
Continuum damage model

[Ladevèze et al, 1992, 2000 2006]
[Lubineau et al, 2008]
[Maimi et al, 2006]
[Camanho et al, 2007]
[Huchette, 2005] [Laurin et al, 2013]
[Germain, 2020]



LMT Mesomodel [Abisset, 2012]

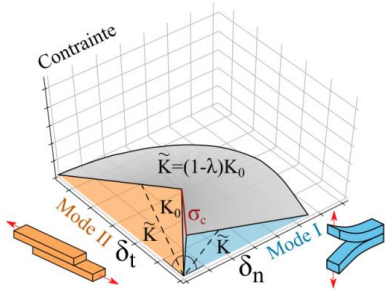
Continuum damage models, better suited to our sense for identification and industrial transfer

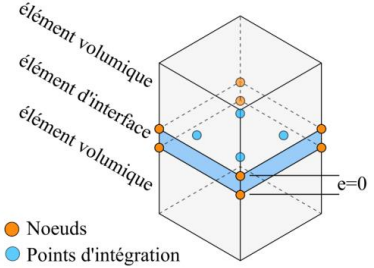


Interface modelling

Cohesive zone model for delamination

[Alfano et al, 2001]
[Camanho et al, 2002]
[Turon et al, 2007 2010]
[Vandellos, 2011]





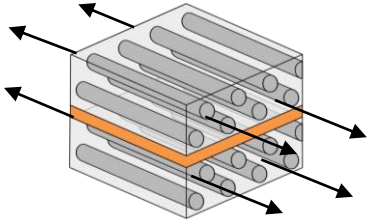
Consensus on CZM for delamination analysis

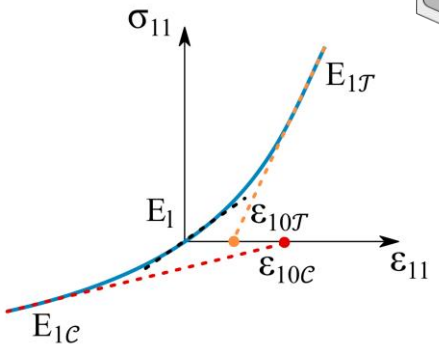
ORFM material behaviour

$$\sigma = \tilde{C} : (\varepsilon - \varepsilon_{nl} - \varepsilon_{th})$$

Non-linear elasticity

In the fibre direction

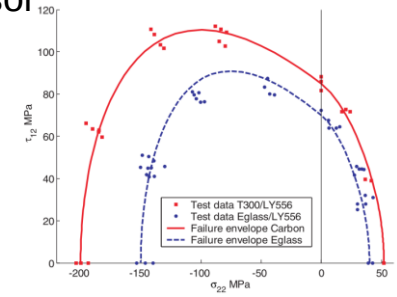




Transverse cracking and fibre failure

Rate dependance introduced through compliance/stiffness tensor

Transverse cracking



In plane failure criteria [Laurin et al, 2007]

Softening fibre failure law

Regularization and additional numerical difficulties

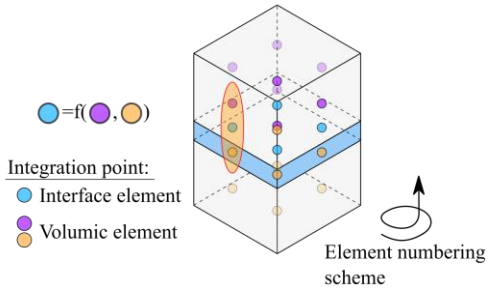
Development of a numerical framework to couple damage with delamination

Numerical damage coupling framework

Transverse cracking / delamination

Build a connectivity table:

- Upper / lower interface element neighbour
- Create a datastructure to pass integration point variables *DATACONTAB*



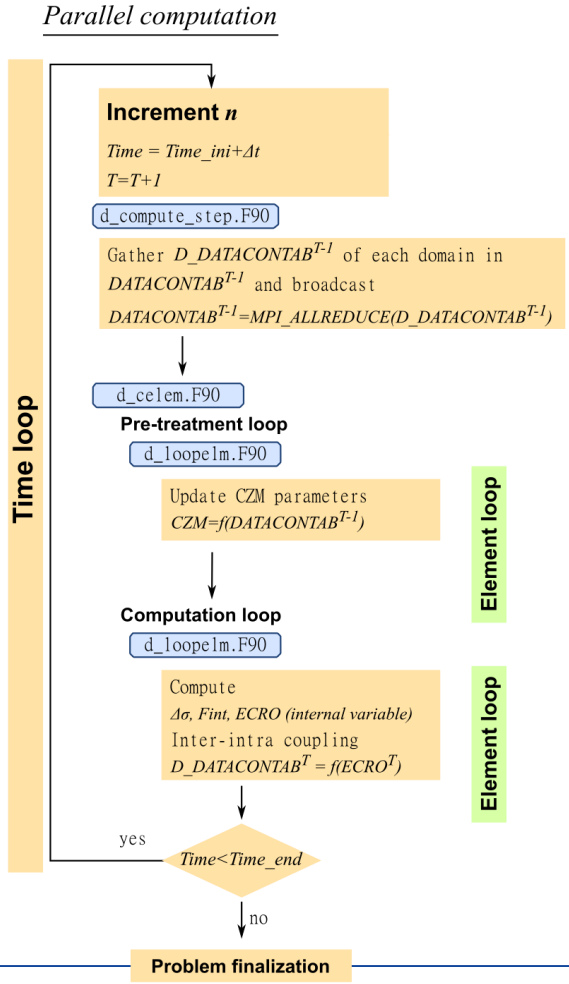
Gather *D_DATACONTAB* and broadcast *DATACONTAB (MPI)*

Get in the pre-treatment loop:

- Update the interface element law based on the ply element values

Get in the Computation loop:

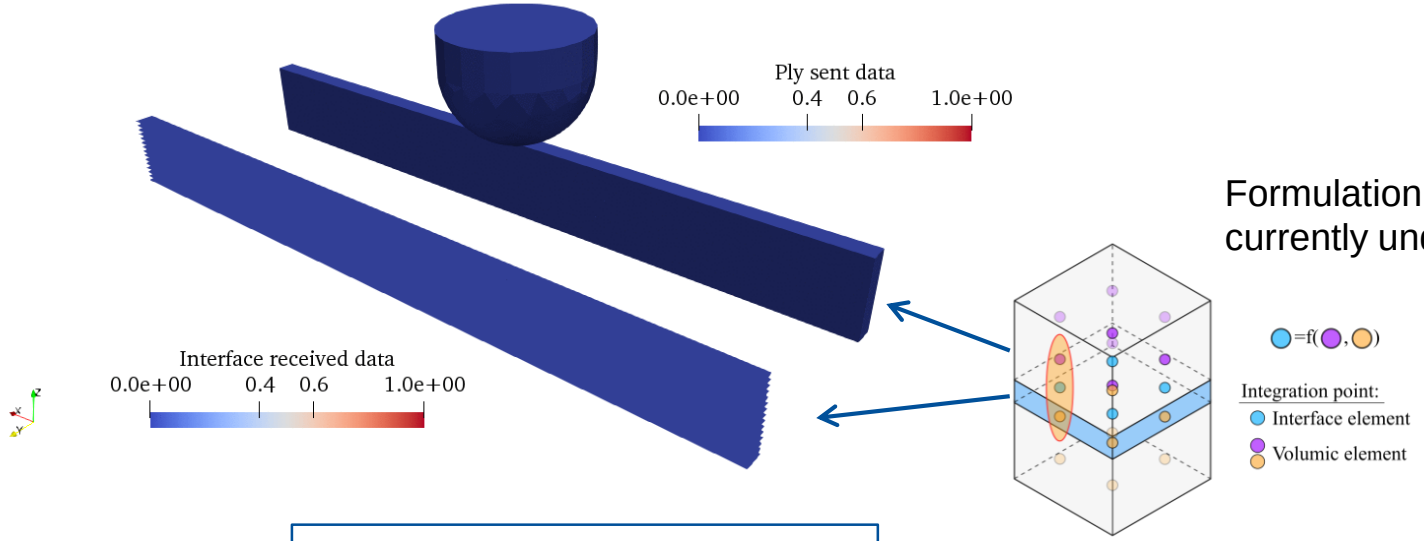
- Update Fint and internal variables, fill *D_DATACONTAB*



Numerical damage coupling framework

Transverse cracking / delamination

Data transfer visualisation on a three point bending specimen



Formulation of a coupling law is currently under investigation

Development will soon be pushed in the master branch of Europlexus

ORFM material behaviour

$$\sigma = \tilde{C} : (\varepsilon - \varepsilon_{nl} - \boxed{\varepsilon_{th}})$$

Thermal residual strain

Cooling phase in the manufacturing process (slow)

Anisotropy of thermal coefficient expansion,

Stresses always present in multidirectional laminate

$$\varepsilon_{th} = \begin{bmatrix} \alpha_L \\ \alpha_T \\ \alpha_T \\ 0 \\ 0 \\ 0 \end{bmatrix} (T - T_0)$$

To our knowledge, never been accounted for in simulations using an explicit solver

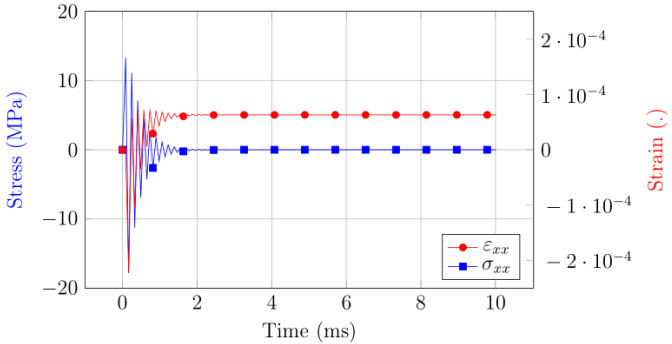
Important feature for damage and failure prediction:
~25-30MPa while the transverse strength is approx. 60-70MPa …

Instant residual thermal strain

Direct computation in the material law

Computation on a single element (CUBE)

$$\varepsilon_{th} = \begin{bmatrix} \alpha_L \\ \alpha_T \\ \alpha_T \\ 0 \\ 0 \\ 0 \end{bmatrix} (T - T_0)$$



Oscillations of the stresses

High frequencies due to direct computation

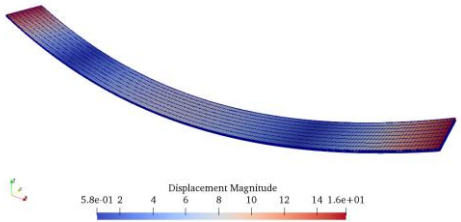
Progressively damped by the element

Instant residual thermal strain

Direct computation in the material law, application to a [0/90] laminate

Explicit simulation

- 10080 elements CUBE (reduced integration)
- Quasi-static damping
- 12 domains



Time: 15905s~4h25
Important number of increment to obtain a stationnary state
Critical time step is a drawback here

Instant residual thermal strain

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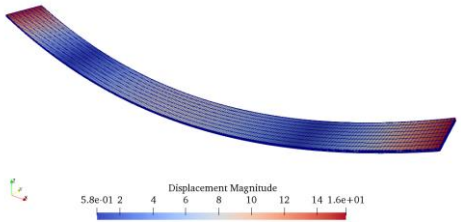

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Important number of increment to obtain a stationnary state
Critical time step is a drawback here

Implicit simulation (ZSet)

- Fully integrated elements
- Quasi static simulation
- 1 domain, 1 core

Time: 11s

Speed up > 1445 wrt explicit simulation

Equilibrium and STATIONNARITY

Instant residual thermal strain

Direct computation in the material law, application to a [0/90] laminate

Explicit simulation

- 10080 elements CUBE (reduced integration)
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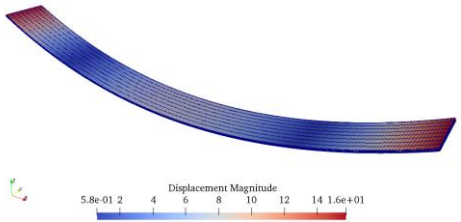

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Implicit simulation (ZSet)

- Fully integrated elements
- Quasi static simulation
- 1 domain, 1 core

Time: 11s

Speed up > 1445 wrt explicit simulation

Equilibrium and STATIONNARITY

Can I use results from implicit simulations to start my explicit simulations ???

Presentation plan

- **Overview of ONERA activities**

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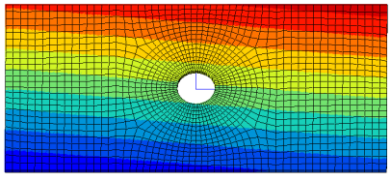
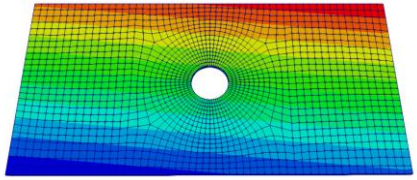
Implicit toward explicit simulations: Strategy n° 1

1) Compute residual thermal stresses



Displacement field U1

2) Extract displacement field; Apply it in Europlexus; Instant εth computation in the law; No external loading



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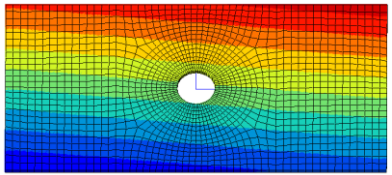

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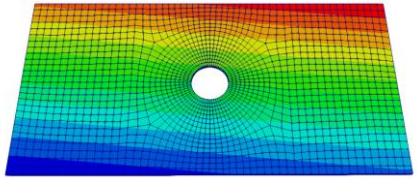
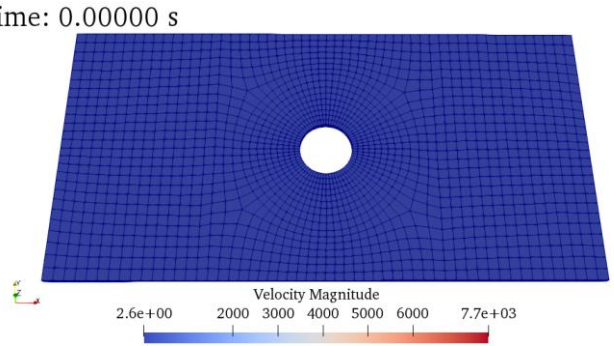


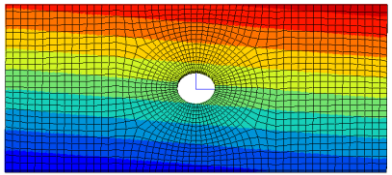
3) Oscillations of the velocity field → not a stationnary state



Reason:
- **Δσ on the first time step**
- **→ ΔFint → a → v → u**

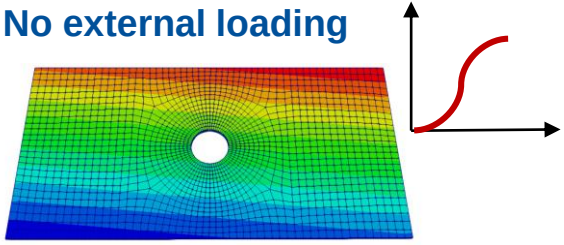
Implicit toward explicit simulations: Strategy n° 2

1) Compute residual thermal stresses



Displacement field U1

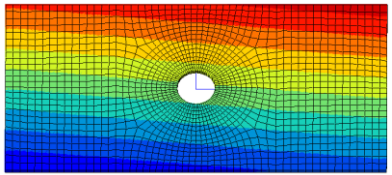
2) Extract displacement field; Progressive application of U and εth with time; No external loading



No inertial effect, I enforce each point displacement

Implicit toward explicit simulations: Strategy n° 2

1) Compute residual thermal stresses



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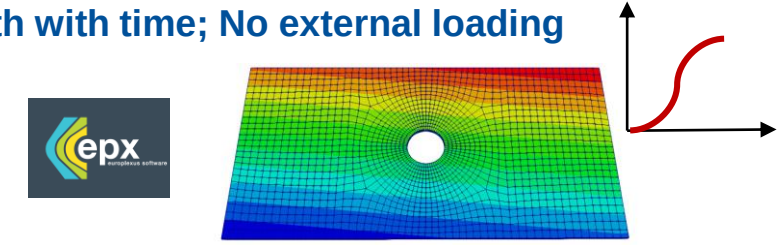
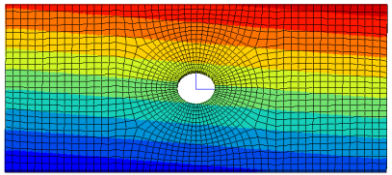


No inertial effect, I enforce each point displacement

3) Initialize a second Europlexus simulation with the previous one
INIT ALICE 10
No external loading

Implicit toward explicit simulations: Strategy n° 2

1) Compute residual thermal stresses



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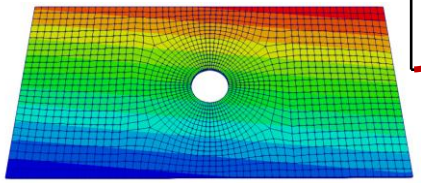

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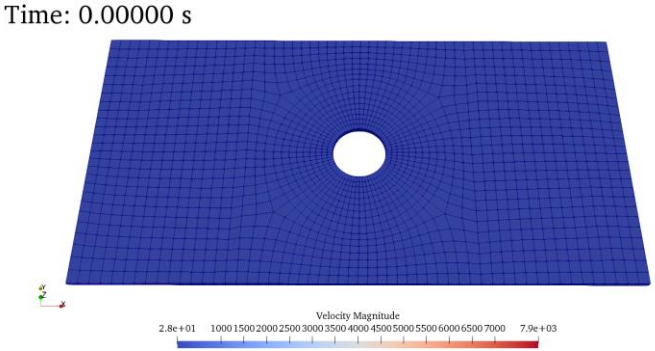

Some troubles are persistant
Still no stationnarity …
Lots of additional tricks, method clearly lacks of robustness

Implicit toward explicit simulations: Strategy n° 3

1) Initialisation by the material behaviour and the stresses *CONT*

Law equivalence through ε_{comp}

- Assumption: no damage occurs (perspective)

$$\sigma = \tilde{C} : (\varepsilon_{ZSet} - \varepsilon_{nl} - \varepsilon_{th}) = \tilde{C} : (\varepsilon_{EPX} - \varepsilon_{nl} + \varepsilon_{comp})$$

$$\sigma_{th} = C_0 : (\varepsilon - \varepsilon_{nl|\sigma th} + \varepsilon_{comp}) = C_0 : (\varepsilon(\underline{u}_{\sigma th}) - \varepsilon_{nl|\sigma th} - \varepsilon_{th})$$

$$\varepsilon_{comp} = S_0 : \sigma_{th} + \varepsilon_{nl|\sigma th}$$

Implicit toward explicit simulations: Strategy n° 3

1) Initialisation by the material behaviour and the stresses *CONT*

Law equivalence through ε_{comp}

- Assumption: no damage occurs (perspective)

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$$\varepsilon_{comp} = S_0 : \sigma_{th} + \varepsilon_{nl|\sigma th}$$

Subtelty: 2 stress vector to be managed:

- Stress of the ply (criteria, damage, non-linearity)

Implicit toward explicit simulations: Strategy n° 3

1) Initialisation by the material behaviour and the stresses *CONT*

Law equivalence through ε_{comp}

- Assumption: no damage occurs (perspective)

$$\sigma = \tilde{C} : (\varepsilon_{ZSet} - \varepsilon_{nl} - \varepsilon_{th}) = \tilde{C} : (\varepsilon_{EPX} - \varepsilon_{nl} + \varepsilon_{comp})$$

$$\sigma_{th} = C_0 : (\varepsilon - \varepsilon_{nl|\sigma th} + \varepsilon_{comp}) = C_0 : (\varepsilon(\underset{\sim}{u}_{\sigma th}) - \varepsilon_{nl|\sigma th} - \varepsilon_{th})$$

$$\varepsilon_{comp} = S_0 : \sigma_{th} + \varepsilon_{nl|\sigma th}$$

Subtelty: 2 stress vector to be managed:

- Stress of the ply (criteria, damage, non-linearity)
- Stress for Fint (exclude the stationnary reference state) $a = M^{-1}(F_{ext} - F_{int})$

$$\sigma_{CD-Scheme} = \tilde{C} : (\varepsilon_{EPX} - \varepsilon_{nl} + S_0 : \sigma_{th} + \varepsilon_{nl|\sigma th}) - \tilde{C} : (\varepsilon(\underset{\sim}{u}_{\sigma th}) - \varepsilon_{nl|\sigma th} - \varepsilon_{th})$$

$$\sigma_{CD-Scheme} = \tilde{C} : (\varepsilon_{EPX} - \varepsilon_{nl} + S_0 : \sigma_{th} + \varepsilon_{nl|\sigma th} - S_0 : \sigma_{th})$$

$$\sigma_{CD-Scheme} = \tilde{C} : (\varepsilon_{EPX} - \varepsilon_{nl} + \varepsilon_{nl|\sigma th})$$

Implicit toward explicit simulations: Strategy n° 3

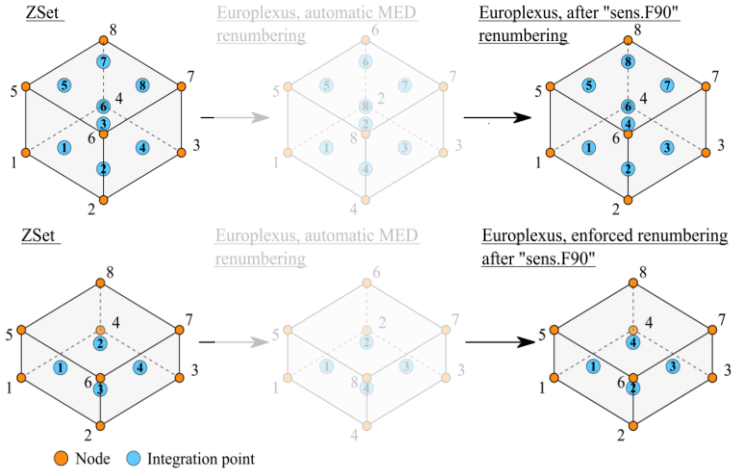
2) Integration point mapping

Extract each stress component for each integration point in Zset

Integration point mapping:

- C3D8 / CUB8
- I3D8 / INT8
- C3D6 / PR6

I use MED file for Europlexus



Implicit toward explicit simulations: Strategy n° 3

2) Integration point mapping

Extract each stress component for each integration point in Zset

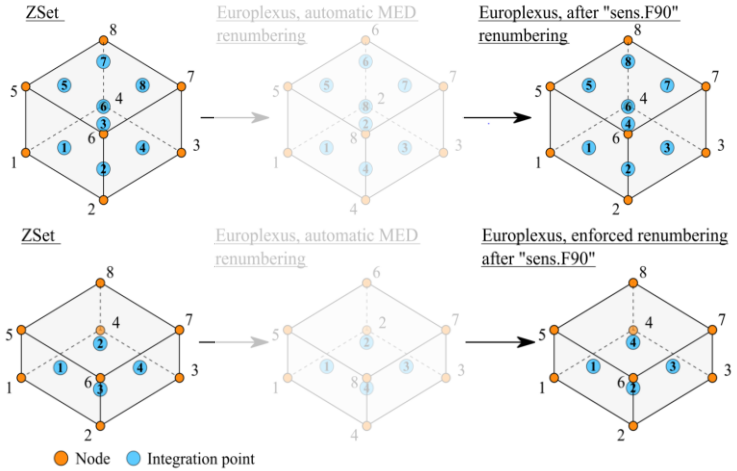
Integration point mapping:

- C3D8 / CUB8
- I3D8 / INT8
- C3D6 / PR6

Automatic initialisation file writer with correct mapping

INIT CQST

I use MED file for Europlexus



Europlexus file:

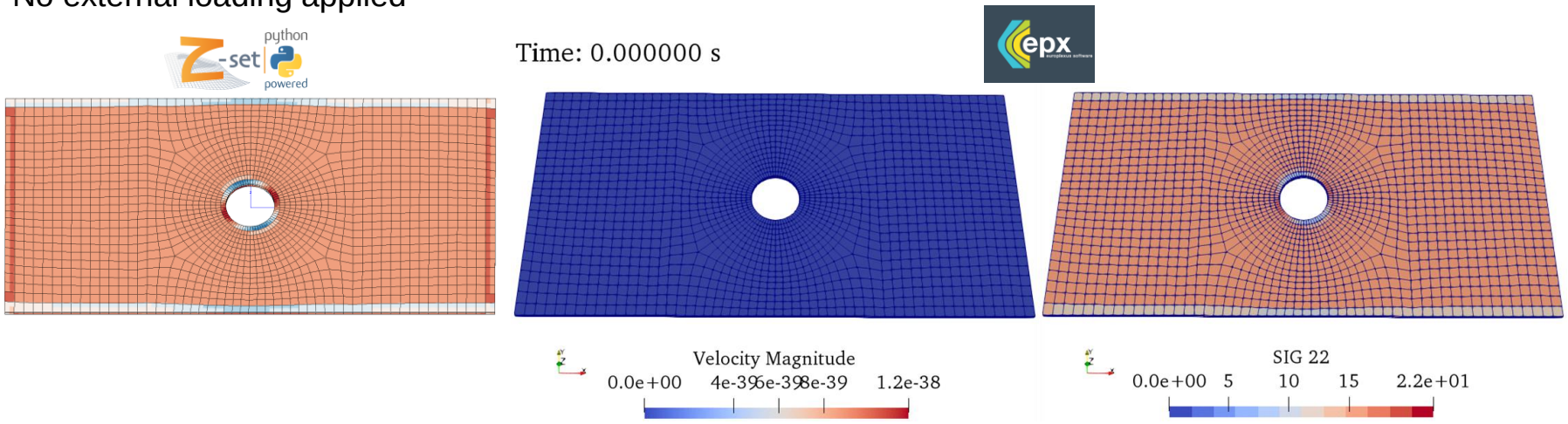
```
$ ************  GROUP E FUNCTIONS AND INITIAL CONDITIONS *************
$ ********************************************************************************

INCLUDE 9! File containing stresses has this file name with '.msh' extension
```

```
INIT
CQST 1 -3.989907026290894 37.978317260742188 3.502702474594116
 -5.171805381774902 -6.953680992126465 6.911044120788574 0 0
LECT 1 TERM
CQST 2 -9.553457260131836 33.996635437011719 -2.203387260437012
 -4.478072643280029 -1.780829548835754 3.736872196197510 0 0
LECT 1 TERM
.
RETOUR
```

Validation of the proposed strategy

Stress initialisation with *CONT, INIT CQST* for each integration point

No external loading applied



*field visualisation;
1 value per integration point in Zset
1 value per cell for Europlexus

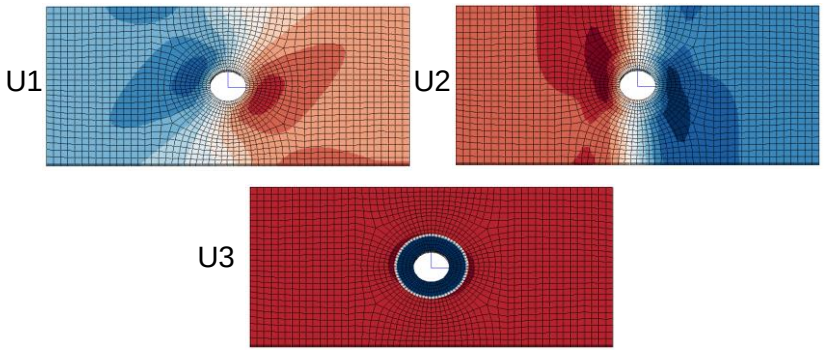
Stationnarity state, velocity field remains null

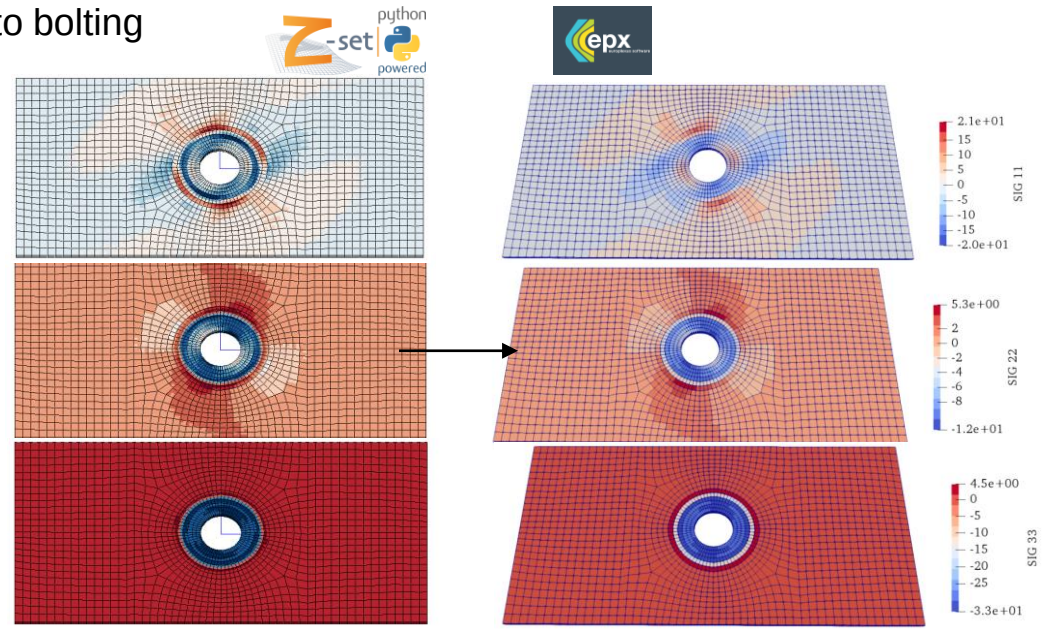
Versatility of the proposed strategy

Impose a generic equilibrium state to start en explicit simulation, as long as no damage occurs

Exemple: Compression around hole due to bolting

Displacement field solution of equilibrium





*field visualisation;
1 value per integration point in Zset
1 value per cell for Europlexus

Versatility of the proposed strategy

Impose a generic equilibrium state to start en explicit simulation, as long as no damage occurs

Exemple: Compression around hole due to bolting

Displacement field solution of eq

U1

U2

U3

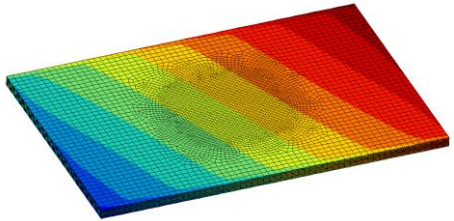
Transfer are fully automated through a module named Europython

Be patient, live demo is on its way !

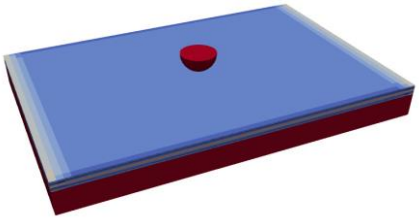
*field visualisation;
1 value per integration point in Zset;
1 value per cell for Europlexus

Application: Rigid impact on a laminate

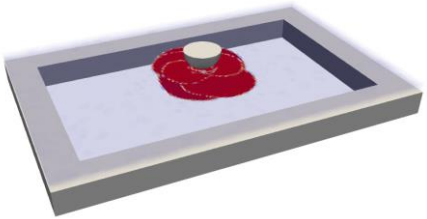
Residual thermal stresses



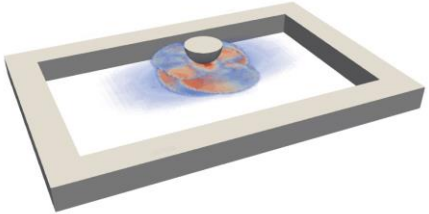
Impact



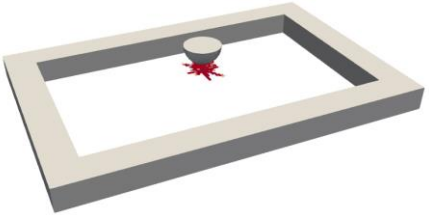
Initial stress



Delamination



Transverse cracking

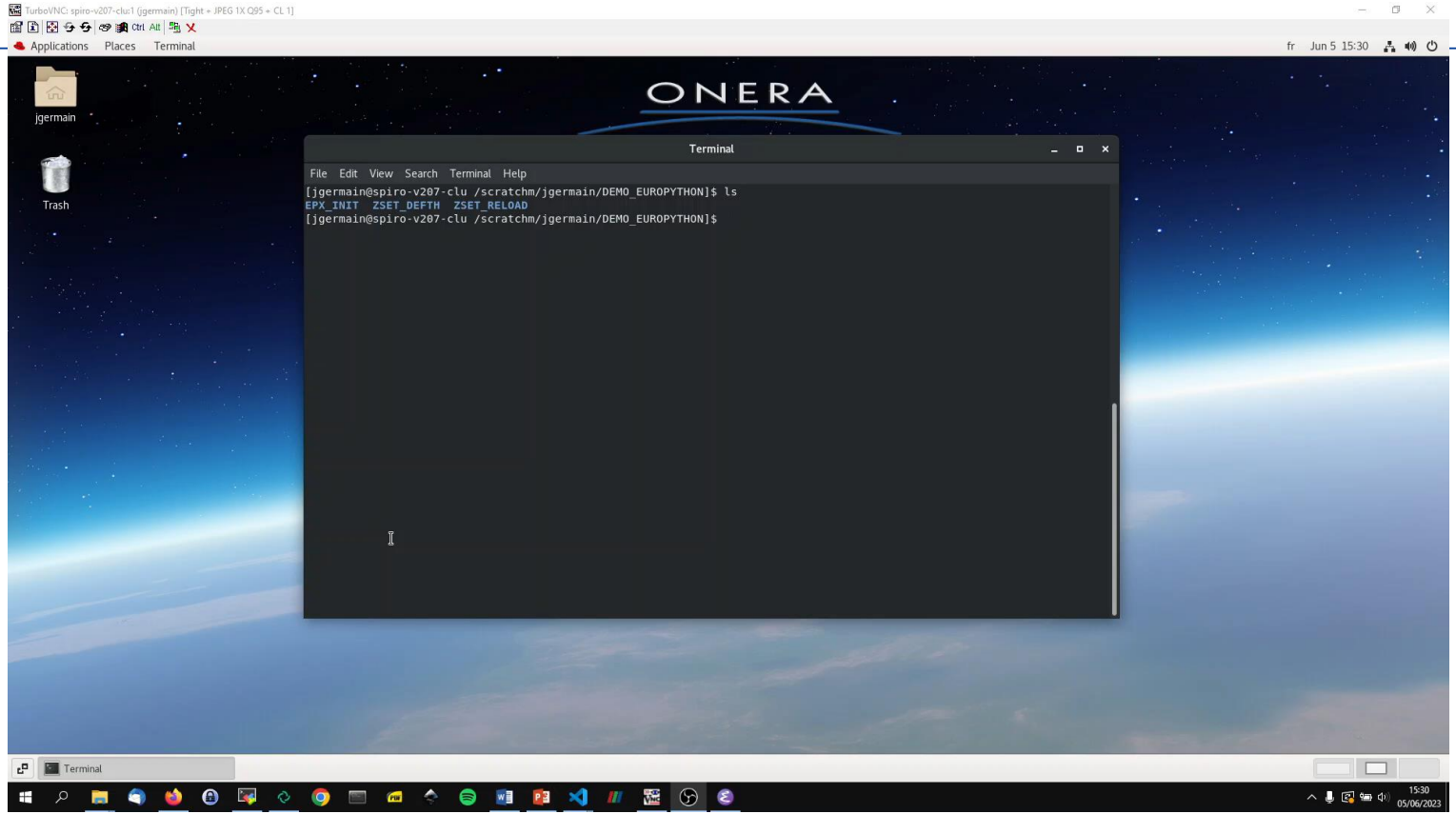


Fibre failure

*Numerical difficulties:

- Regularization and dissipated energy control
- High frequencies due to important loss of stiffness

« Script free » automated procedure with Europython module developped



Conclusion:

Chaining finite element code

- Development of methods to use the most adapted solver to the considered loading
  - Numerically efficient (speed up > 1400)
  - Methodology based on stresses (it should work with strain, but it is not managed the same way in EPX)
  - Law dependent …, additional variables are to be stored

- Transfer remain « partial » **But, probably sufficient … ?**
  - Zset → Europlexus:
    - Stresses for each integration point
    - Mesh could be deformed to take into account the inital loading displacement
  - Europlexus → ZSet:
    - Internal variables for each integration point

Perspective:

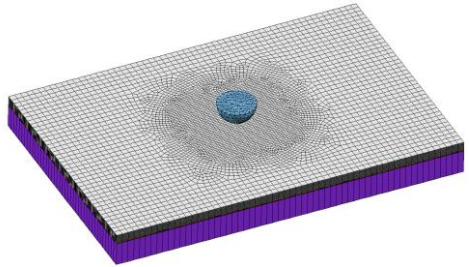
Chaining finite element code

- Initialisation of ECRO **My method cannot be applied if damage occurs prior to the explicit simulation**
  - How to ? EPX as a library could be a way to achieve this.

Discussion with Pascal Bouda around EPX as a library

- Output management
  - I read .listing file in a « smart » way
  - Possiblity to directly have data stored in .npy file will be a more efficient workflow

- Mesh management for multibody problems:
  - Each body not necessarily usefull for each simulation
    - Additional mapping between mesh



Thank you,

Please, feel free for discussion and questions