Overview of the work performed at ONERA on composite materials

F. Laurin

ONERA, the french aerospace lab

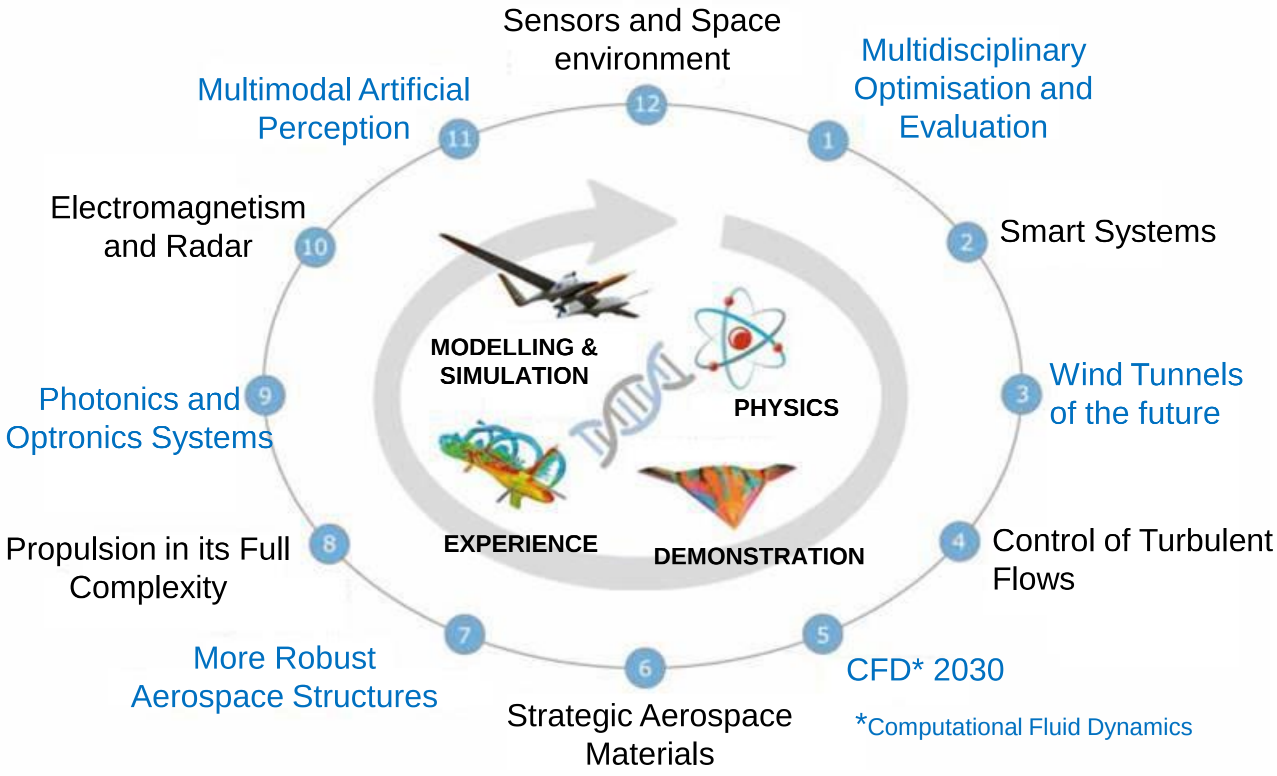
A public enterprise

- Under the supervision of the French Ministry MINISTÈRE DES ARMÉES Liberté Égalité Fraternité
- Largest wind tunnel fleet in Europe
- **€256 million budget** in 2021, including
- **€266 million budget** in 2022
- **2,123 employees** in 2021 including
  1,304 engineers and executives,
  350 doctoral students,
  23 qualified postgraduates
- 113 scientists holding an accreditation to direct research (french HDR)
- 11 new accreditations to direct research

8 locations in France

Scientific knowledge for the future of Aerospace

The 12 ONERA challenges serving Defence, Aeronautics and Space

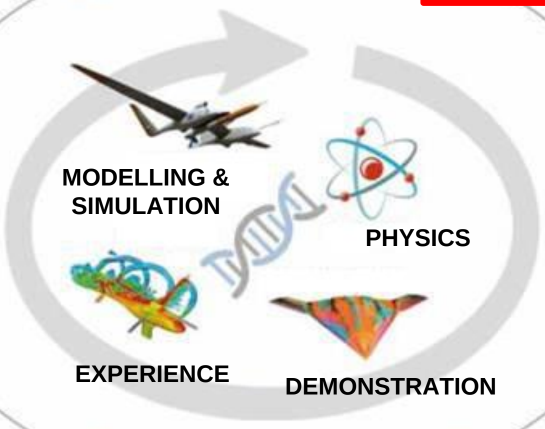


Sylvain Gaultier - ONERA

Scientific knowledge for the future of Aerospace

The 12 ONERA challenges serving Defence, Aeronautics and Space

1. Multidisciplinary Optimisation and Evaluation
2. Smart Systems
3. Wind Tunnels of the future
4. Control of Turbulent Flows
5. CFD* 2030
6. Strategic Aerospace Materials
7. More Robust Aerospace Structures
8. Propulsion in its Full Complexity
9. Photonics and Optronics Systems
10. Electromagnetism and Radar
11. Multimodal Artificial Perception
12. Sensors and Space environment



*Computational Fluid Dynamics

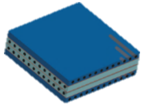
Topics adressed in MAterial and Structures Departement (DMAS)

Sylvain Gaultier - ONERA

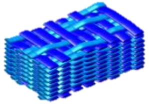
Studied composite materials at ONERA

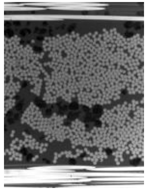
Low temperature

Composites with polymer matrix



Unidirectional plies
2D/3D woven plies





Interesting properties

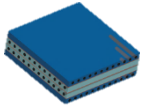
- Multiple damage/failure mechanisms
- High fatigue lifetime (compared to metal)
- High impact sensitivity

Thermoset matrix or thermoplastic matrix

Partners: AIRBUS, DASSAULT, STELIA …

High temperature

Composites with ceramic matrix



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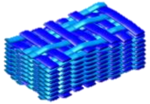
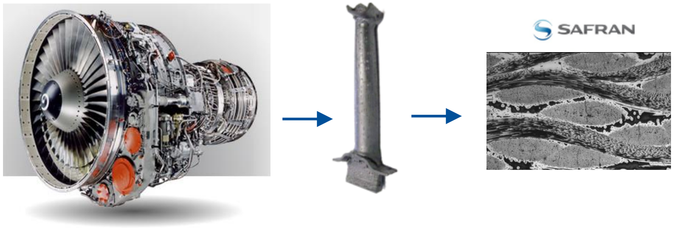




Interesting properties

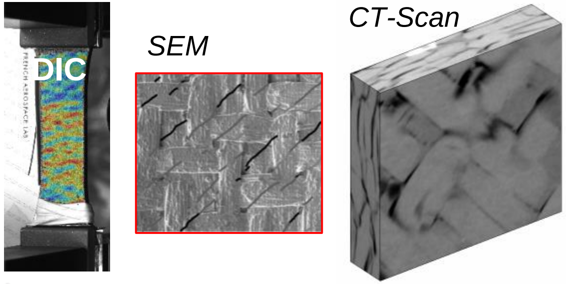
- Good mechanical properties at high temp.
- Sensitive to fatigue loadings
- Durability in severe environment

Sic/Sic, C/C, Oxide/Oxide materials

Partners: SAFRAN, CEA, MBDA …

Content of the presentation

Experiments



Multi-instrumented tests

- *Image correlation, SEM, CT-Scan,*
- *Acoustic emission, IR thermography*

Design of new composite tests

Link between simulation/test

Modelling

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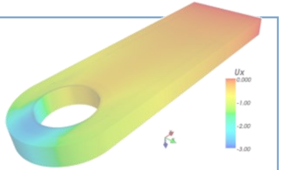
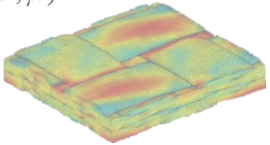




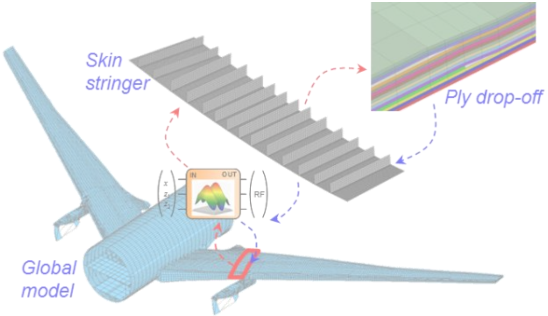
Development of advanced models

- *Damage and failure models*
- *Fatigue lifetime predictions*
- *Impact simulations*

Multi-physical simulation

- *Fire and lightning strike issues*

Design



Design method

- *Lay-up optimisation with constraints*
- *Topological optimisation*
- *Coupled shape and orientation optim.*

Innovative composite structures

- *H2 tank, fractal structures*

3 main topics addressed by the ONERA's composite team

Methodology to detect transverse cracks in laminates

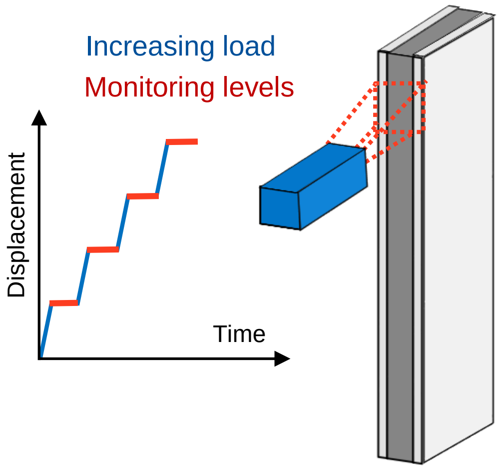
Study of the damage mechanisms

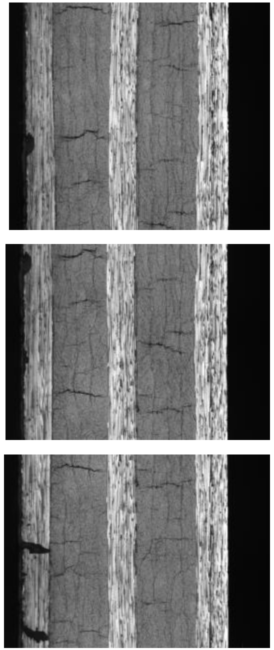
Proposed methodology

- Optical analysis on one polished edge **during loading** (open cracks)
- Assembling many pictures (>100) to obtain high resolution images on a large domain
- Digital image correlation between initial and cracks images *(DeepFlow software)*
- Labelling each crack (orientation, length, …)

Fully automated crack detection method

- Applied on classical Carbon/Epoxy materials
  [Nicol 22], [Patti 22]
- Applied to Carbon/thermoplastic in this study
  [Laurin22]





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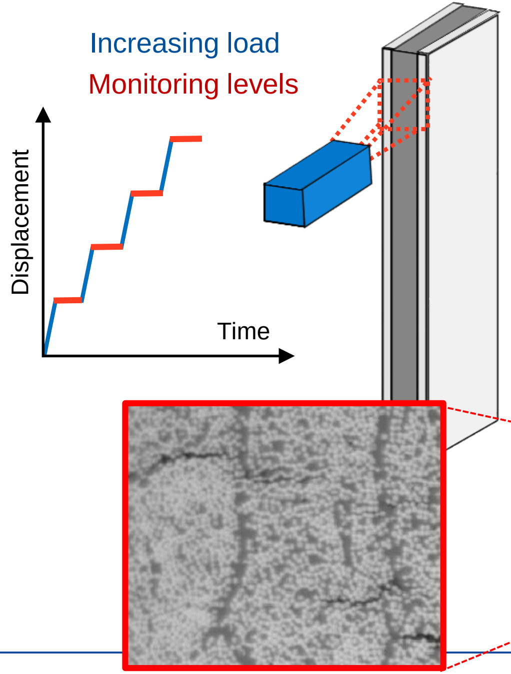

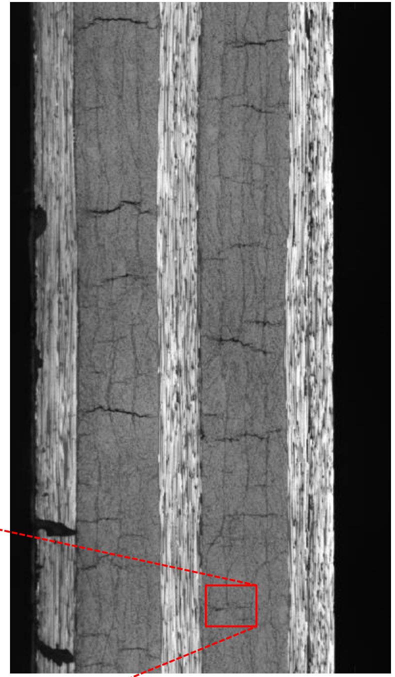

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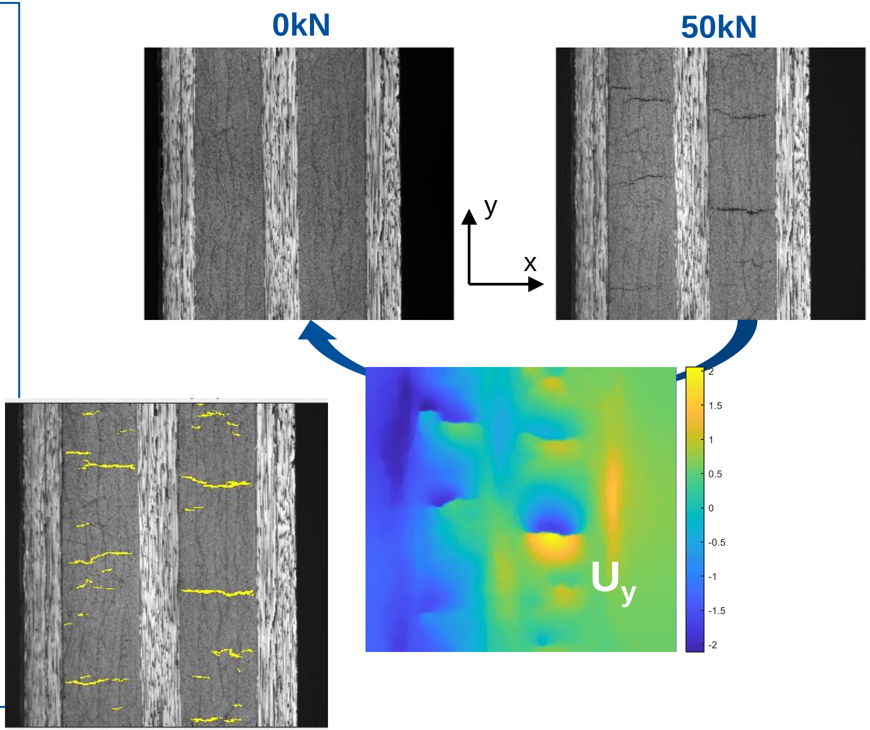

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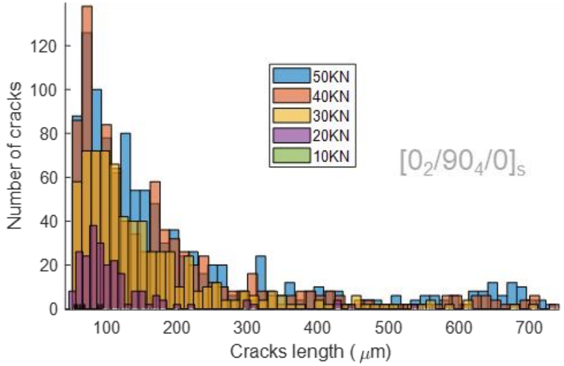
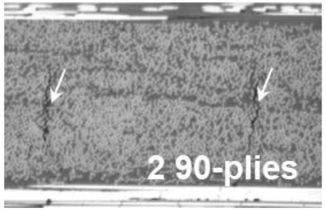
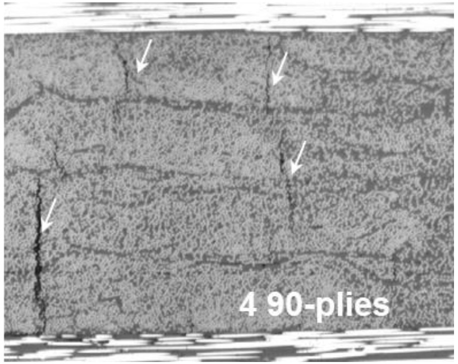


Cross-ply laminates
- $[0/90_2/0/90_2/0]_s$
- $[0_2/90_4/0]_s$





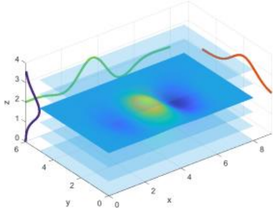
Methodology to detect initial out-of-plane waviness

Initial CT-scan images

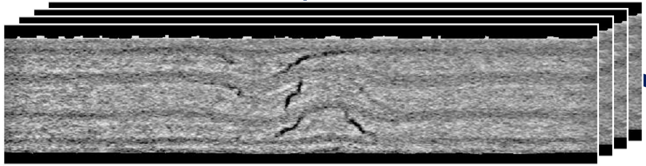
CT-Scan made by LMPS Paris-Saclay

Initial 7 parameters set

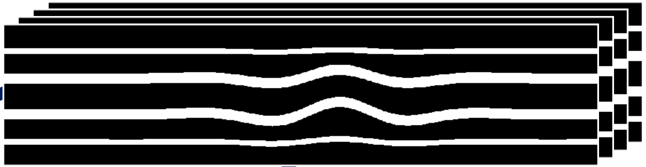
$$Waviness(x,z) = \boldsymbol{A}\cos\left(2\pi\frac{(x-\boldsymbol{x_{0cos}})}{\boldsymbol{\delta}}\right)\exp\left(-0{,}5\frac{(x-\boldsymbol{x_{0exp}})^2}{(\boldsymbol{L}/6)^2}\right)\exp\left(-0{,}5\frac{(z-\boldsymbol{z_0})^2}{(\boldsymbol{z_{aff}}/6)^2}\right)+z$$



Processed images



Fictive parametric tomography



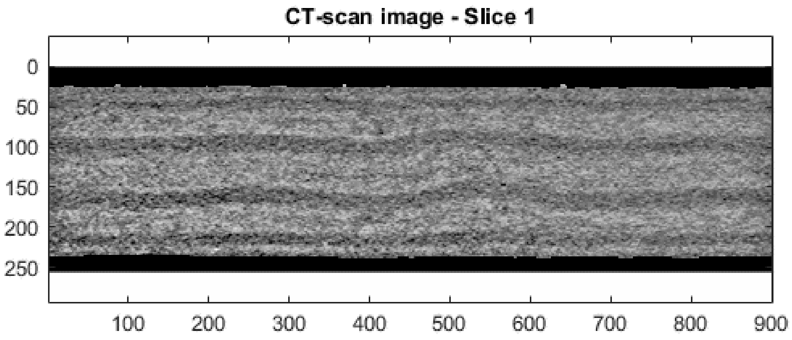
Comparison score

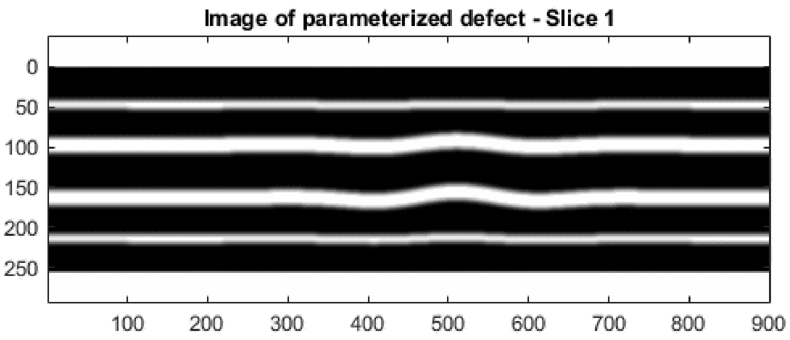
Optim.
(simplex)

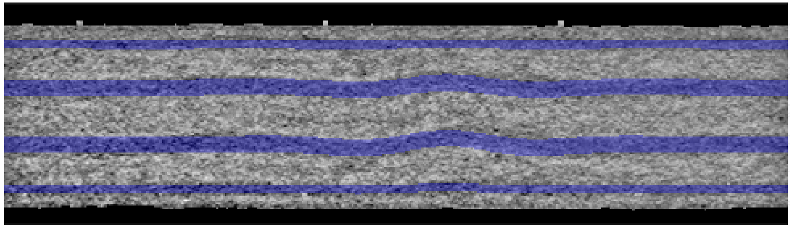
Geometric input parameters

Optimised parameter set

Methodology to detect initial out-of-plane waviness



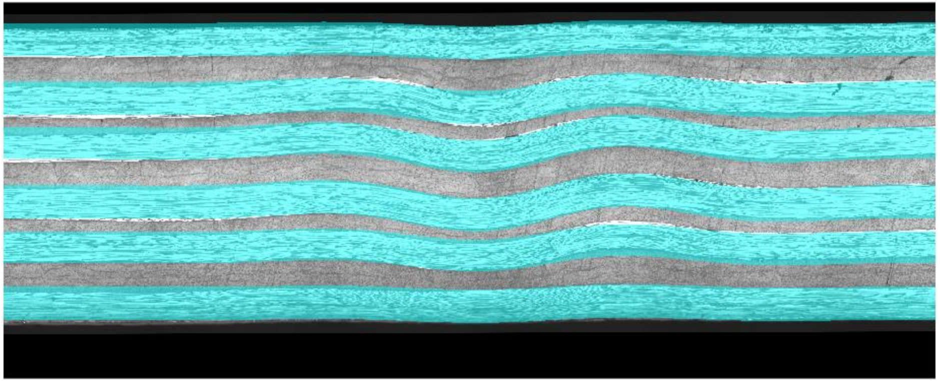


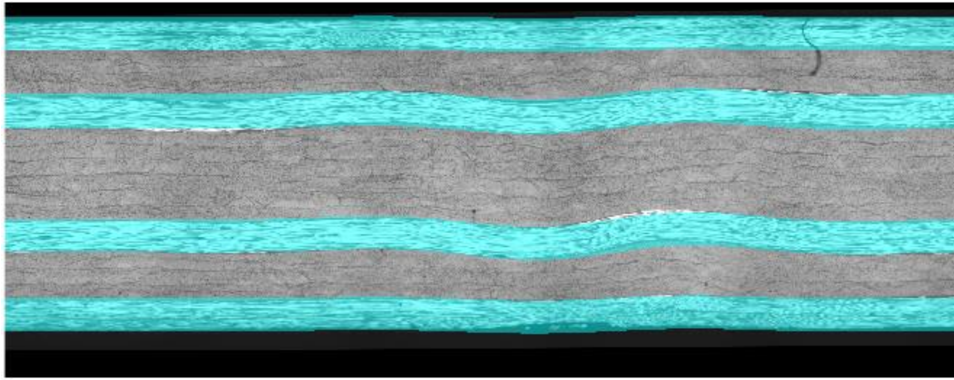


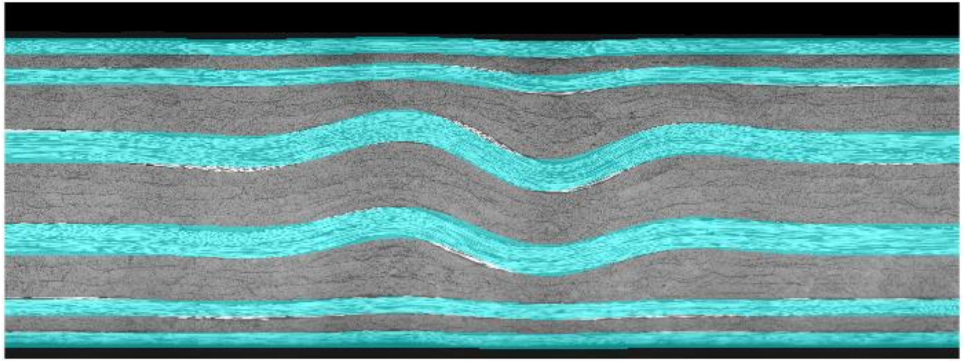
Validation on CT-Scan

📖 [Fougerouse 21]

Methodology to detect initial out-of-plane waviness







Validation on microcuts

📖 [Fougerouse 21]

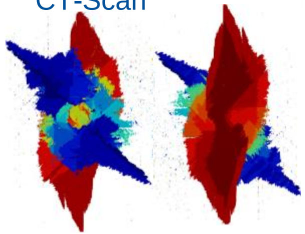
In-situ damage monitoring during impact tests

Study of the impact damage mechanisms

- Optical and thermal superfast cameras during impact tests
- Able to monitor damage evolution during impact tests (<10ms)
- Validation of IR thermography through analysis of CT-Scans

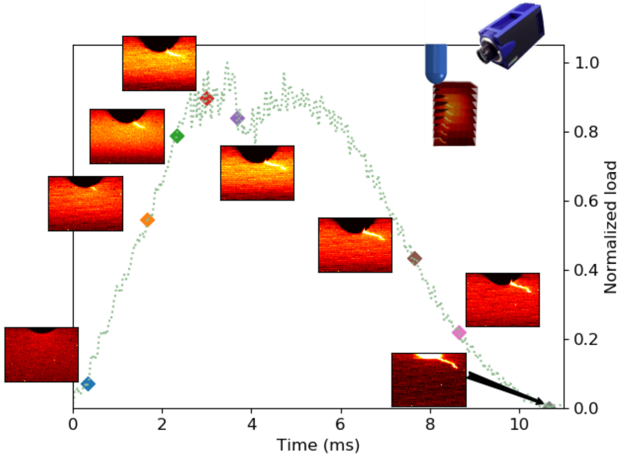
→ **Valuable information to validate finite element simulations**

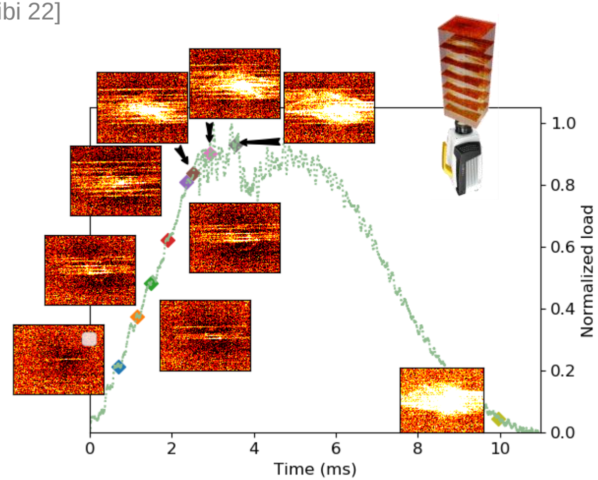
CT-Scan



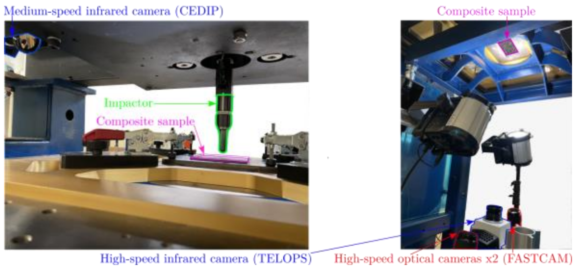
DASSAULT AVIATION

[Chaibi 22]



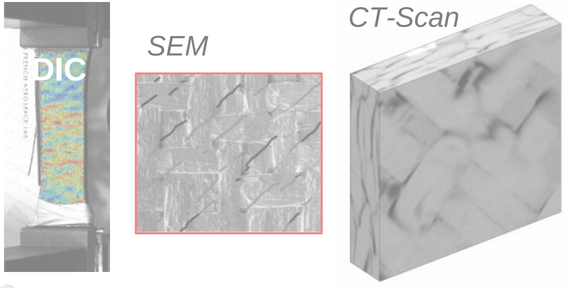


ICA



Content of the presentation

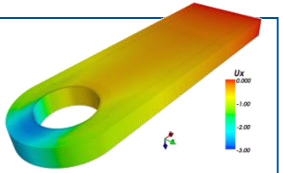
Experiments



- **Multi-instrumented tests**
  - *Image correlation, SEM, CT-Scan,*
  - *Acoustic emission, IR thermography*
- **Design of new composite tests**
- **Link between simulation/test**

Modelling

$$\underline{\sigma} = \underline{\underline{\tilde{C}}} : (\underline{\varepsilon} - \underline{\varepsilon}^{th} - \underline{\varepsilon}^{ve} - \underline{\varepsilon}^{p})$$



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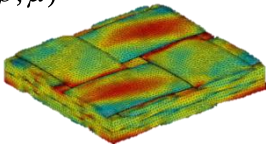

- **Development of advanced models**
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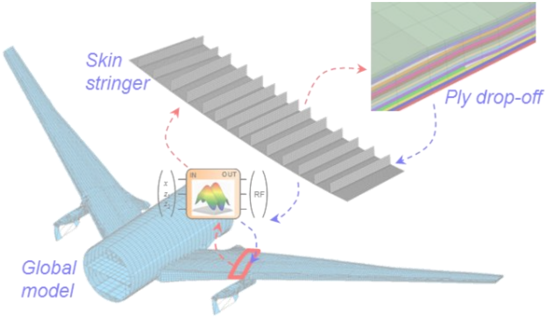
  - *Impact simulations*
- **Multi-physical simulation**
  - *Fire and lightning strike issues*

Design



- **Design method**
  - *Lay-up optimisation with constraints*
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- **Innovative composite structures**
  - *H2 tank, fractal structures*

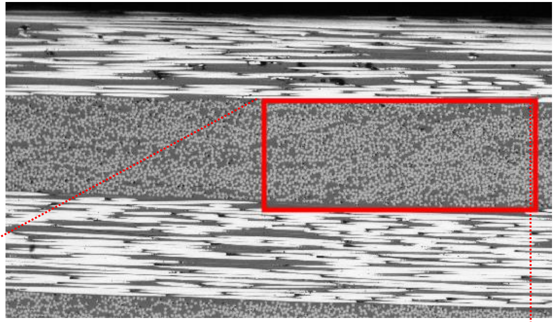
3 main topics addressed by the ONERA’s composite team

Simulation at microscale for comprehension purposes

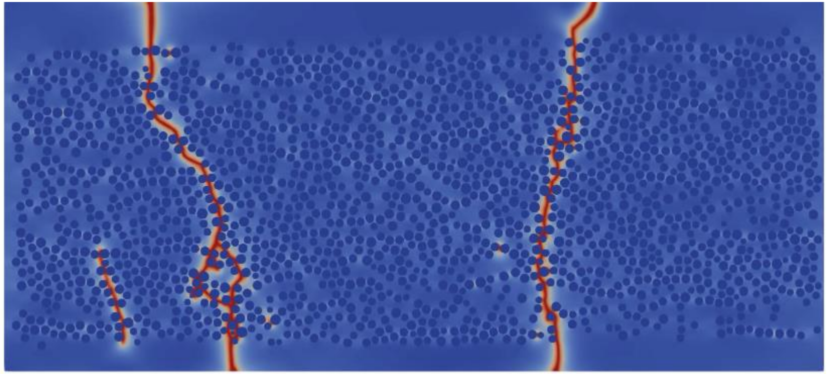
Damage FE simulations

- Extraction of the real microstructure from pictures 📖 *[Benezech 19 , Przybyla 21]*
- Mesh fibres and matrix around (~10 millions degrees of freedom)
- Fibre are linear elastic and **phase-field damage approach** for matrix
- **Massive decomposition domain** method associated to simulation
- **Comprehension** of the damage pattern in thermoplastic matrix composite

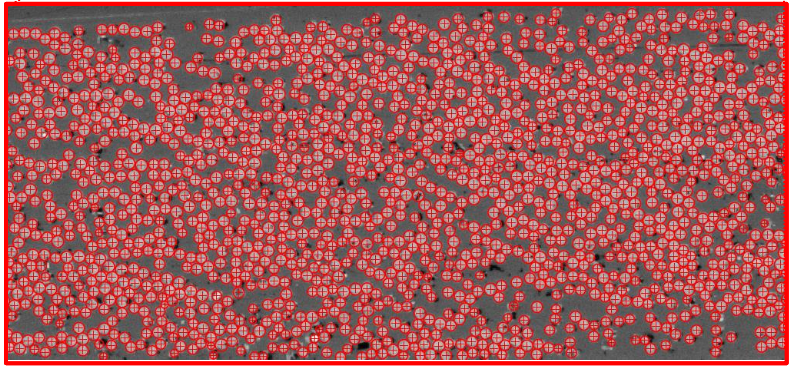
Optical micrography



Phase field simulation (10Mdof-40 domains)



Fibres detection



📖 *[Rannou 21]*

Computational strategy for large composite structures

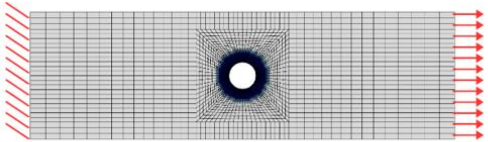
Proposed methodology

Adaptive computational strategy

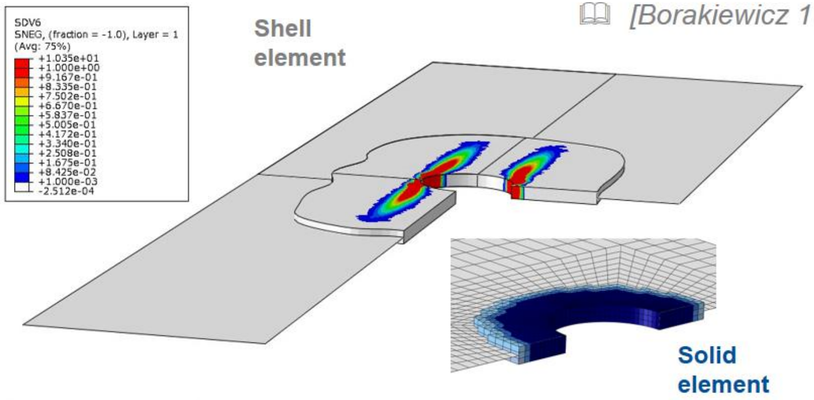
- Shell elements for the structure (hot-spot detection)
- Solid element only in critical areas + NL behaviour
- Evolution of the critical area due to propagation of damage events → Remeshing + field transfer

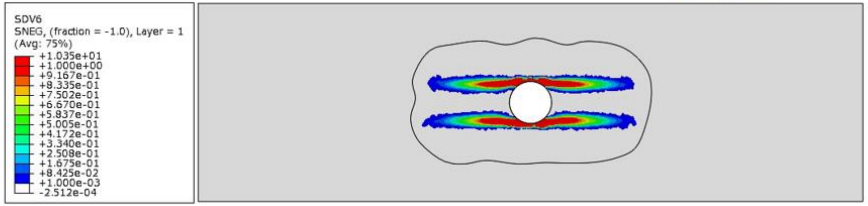
Numerical tools

- Z-set : ***Remeshing + field transfer***
- ABAQUS or Z-set Equilibrium + NL behaviour

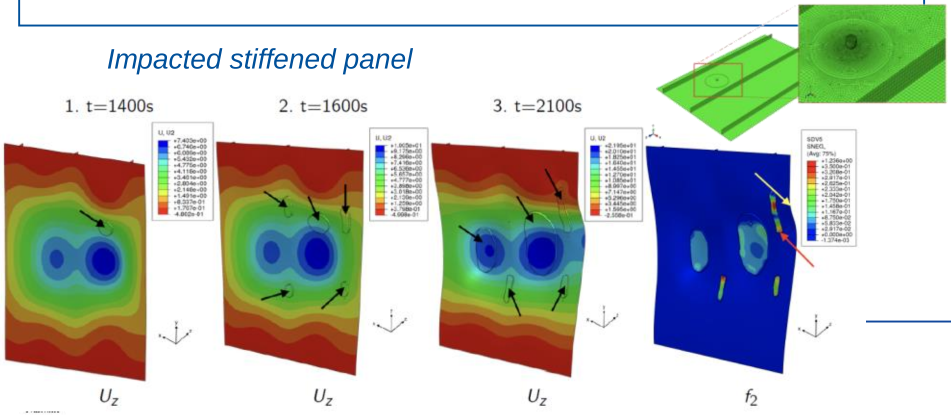


[Borakiewicz 19]





Impacted stiffened panel



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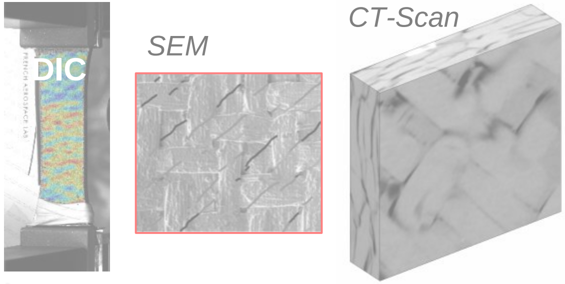

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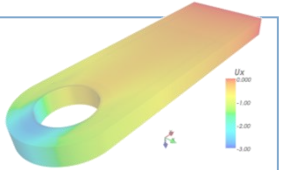

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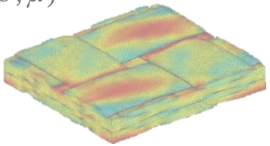

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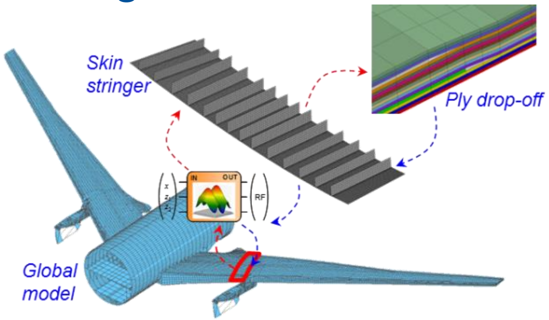

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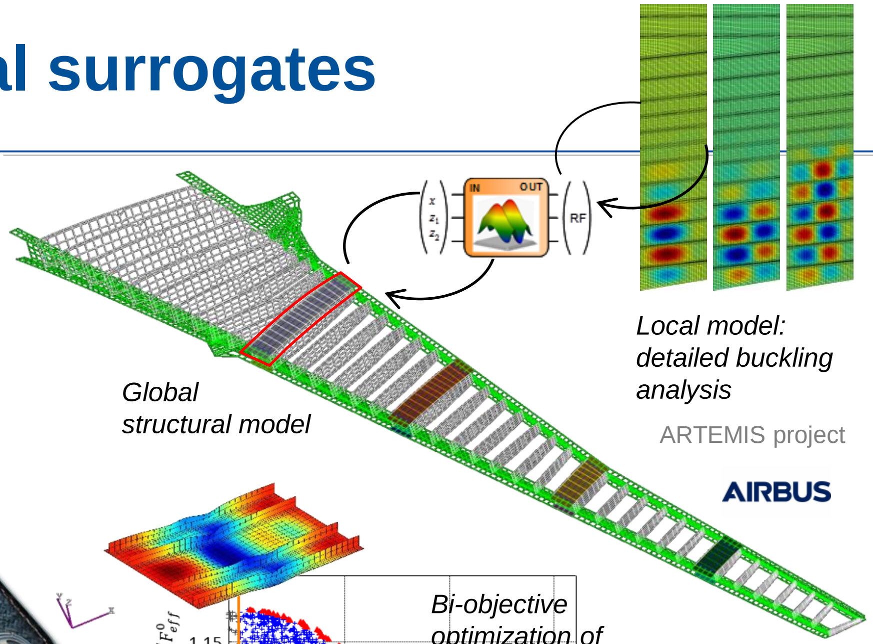
Laminate optimization and global surrogates

Specialized genetic algorithms

- Direct parametrization of the ***ply angles and ply drops***
- Pareto multi-objective optimization
- Handling of laminate design guidelines (symmetry, …)

Computational strategy

- ***Global surrogates***
  failure modes, buckling modes …..
- Design of experiments in LP-space
- MDO process



Global structural model

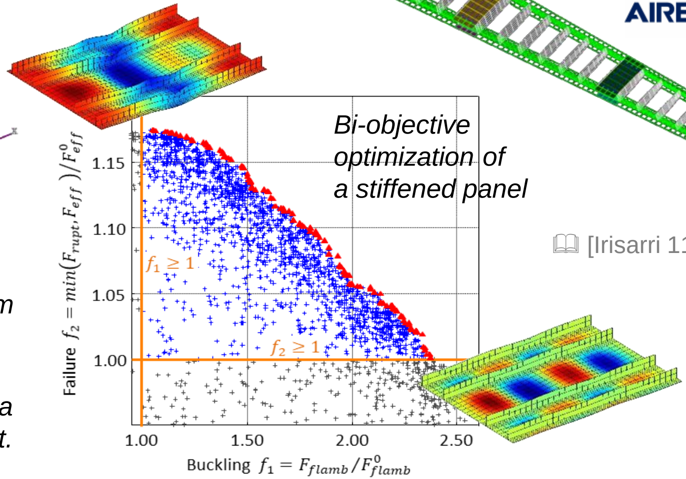
Local model: detailed buckling analysis

ARTEMIS project

AIRBUS

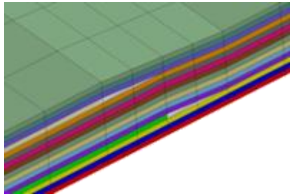
cetim

Automotive suspension arm



Bi-objective optimization of a stiffened panel

📖 [Irisarri 11]



📖 [Lasseigne 15]

Ply drops

📖 [Irisarri 19]

MECANO I&D

Satellite antenna mounting bracket.

Topology optimization for anisotropic materials

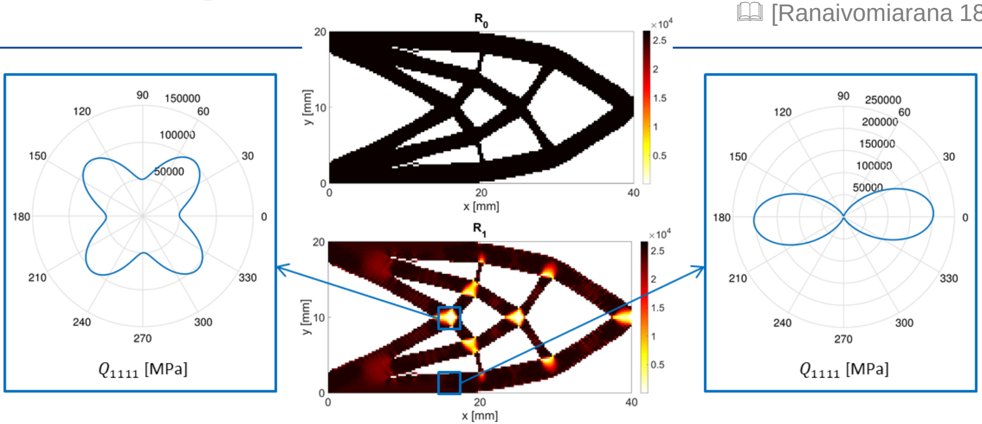
Anisotropy as a design variable

- ***SIMP*** / level-set methods for shape
- Invariant-based parameterization : 2D orthotropic materials or 3D transversely isotropic materials
- ***3D printed cellular materials and structures***

Design criteria

- Compliance minimization
- Mass minimization with stress constraints

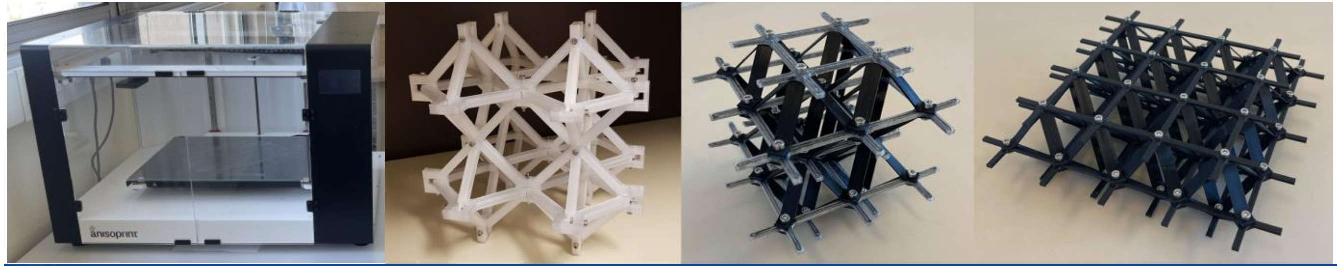
📖 [Ranaivomiarana 18]

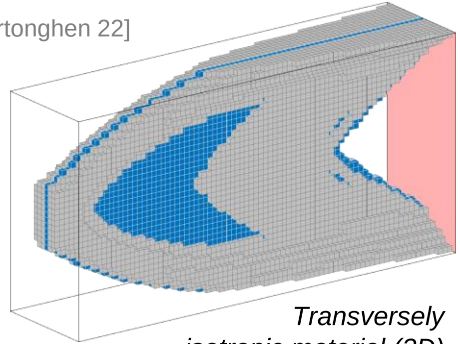


Concurrent density and anisotropy optimization (2D)

📖 [Vertonghen 22]

3D printed multi-material cellular lattice structures



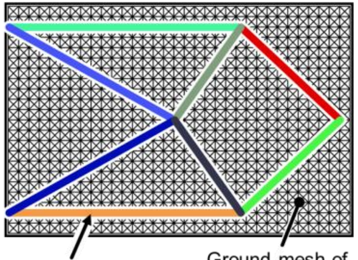


Transversely isotropic material (3D)

Simultaneous optimization of shape and composite layups

Multilevel optimization framework

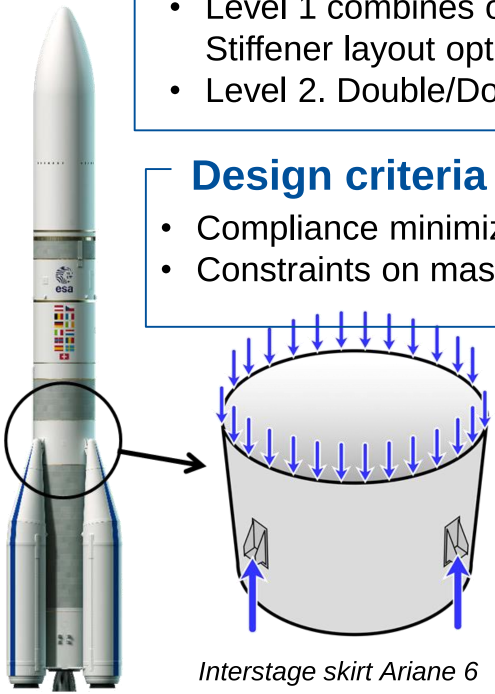
- Level 1 combines optimization of macroscopic properties and shape
  Stiffener layout optimized using a geometric projection method
- Level 2. Double/Double composite laminates or quasi-trivial laminates



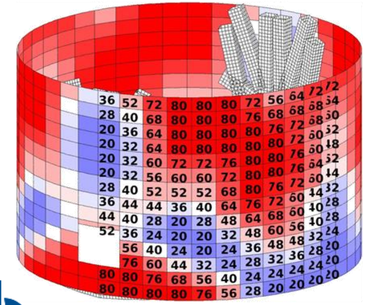
[Savigne 22]

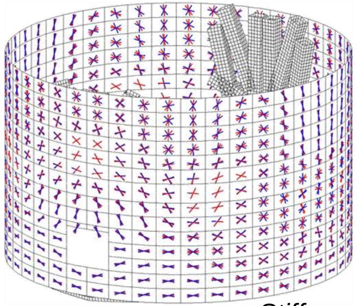
Design criteria

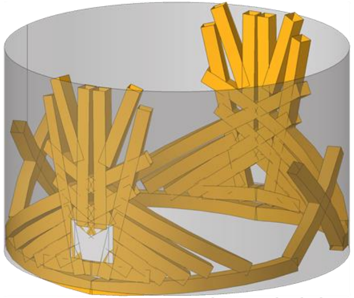
- Compliance minimization
- Constraints on mass, buckling, strength and displacements



Interstage skirt Ariane 6

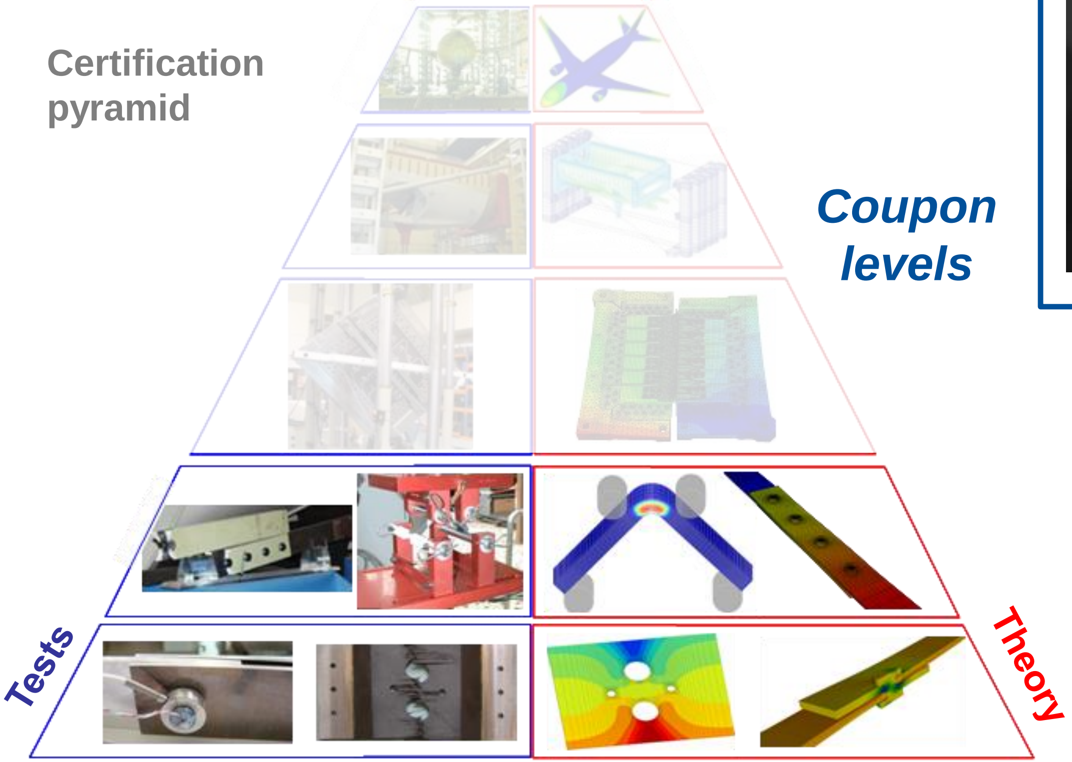




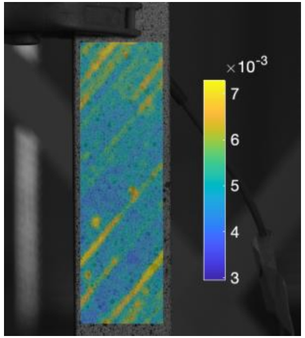


Stiffened structure or corrugated sandwich?
30% mass reduction wrt reference metallic design

Conclusions



Tests at low levels of pyramid



Test on coupons

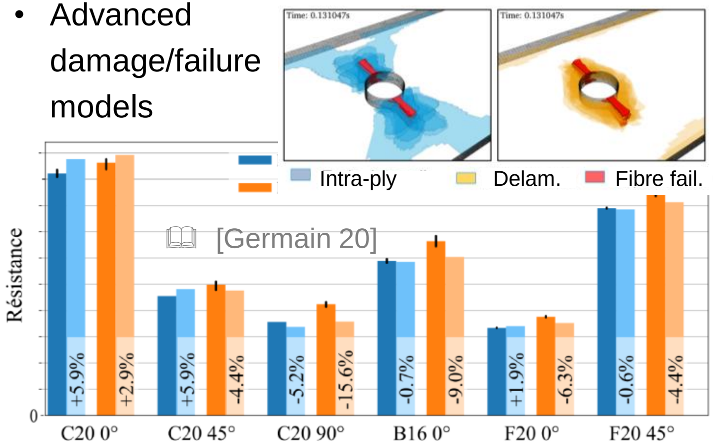
- Multi-instrumentation
- Fine comprehension

Test on structures

- Plain coupons
- Open-hole plates
- L-angle specimens

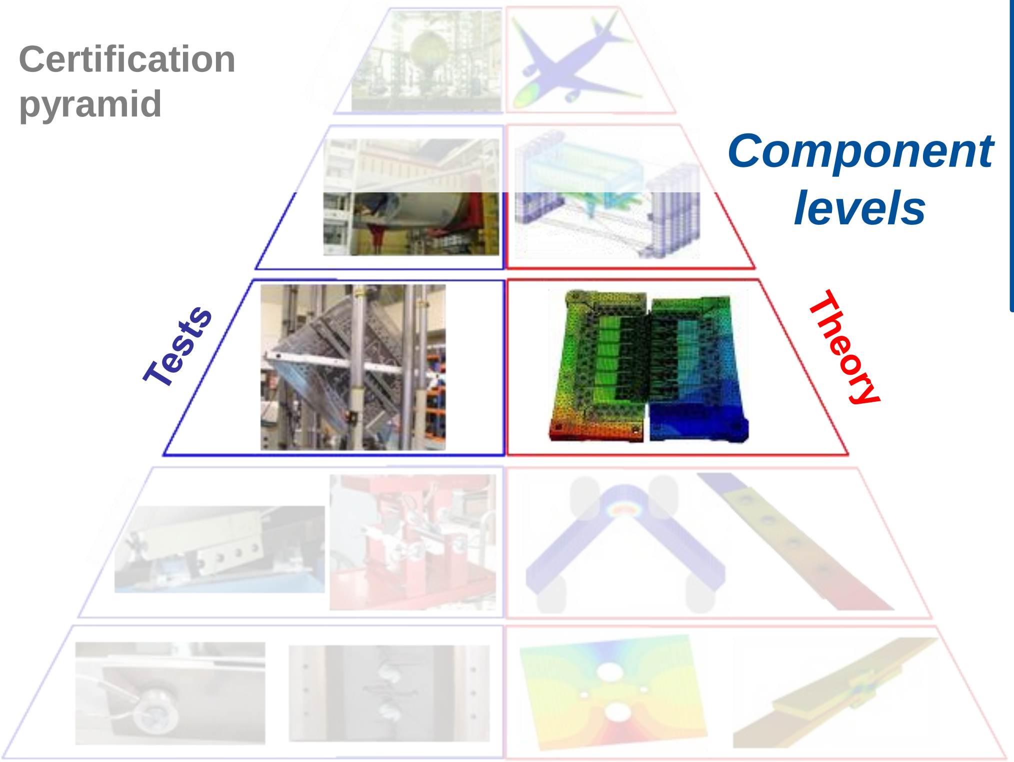
Simulation on structures

- Advanced damage/failure models



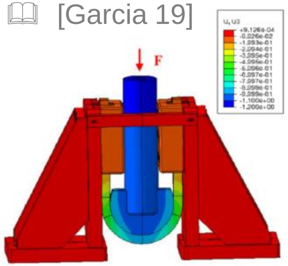
On-going works

Certification pyramid



Components level

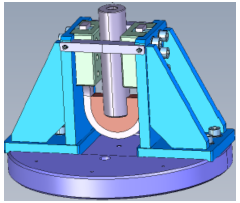
[Garcia 19]

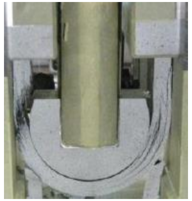


Data capitalization

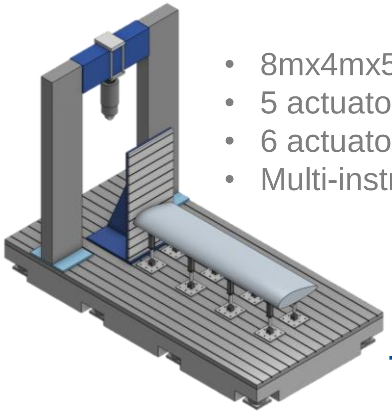
Test on structures

- Multi-instrumentation
- Mastered BCs





JERICHO test platform *(end 2024)*



- 8mx4mx5m platform
- 5 actuators (250kN-1500kN)
- 6 actuators (150kN-250kN)
- Multi-instrumented tests

Test hybridization

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