Advanced Methodology to Evaluate Design of Large Bonded Composite Repair

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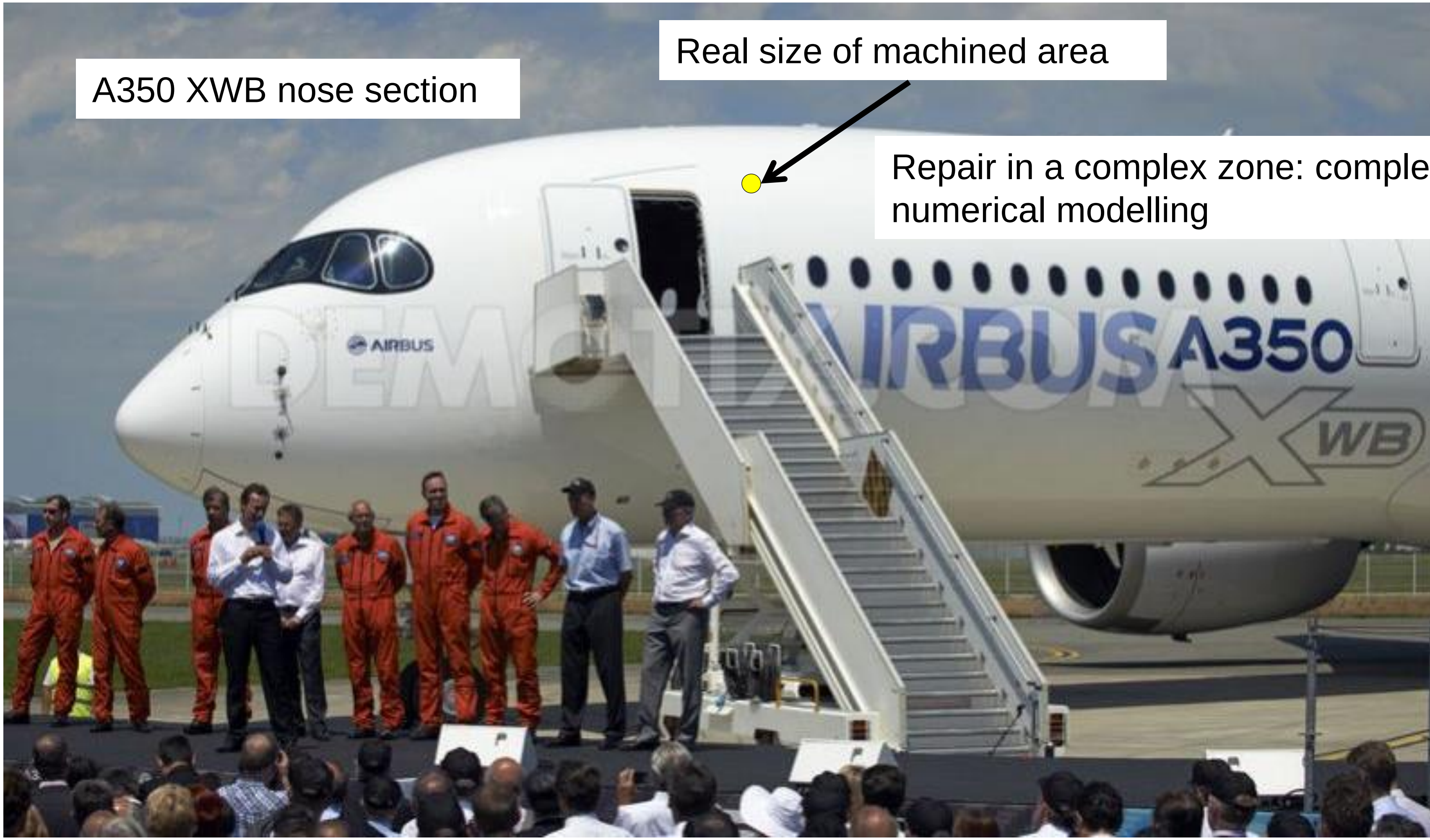
http://www.institut-clement-ader.org/pageperso.php?id=fcollombet&lg=en

Synopsis

1) Development of light usable numerical models for industry
2) Goals and intents: development of generic method for repair/pb. statement/Numerical issues for step lap repair
3) Study of the adhesive film behavior: numerical modelling strategy
4) Numerical modelling for composite step lap repair evaluation: one step shape
5) Studies on coupons: to validate a light modelling strategy
6) Study of the adhesive film behavior: experiments/numerical strategy (shear test)/in house failure shear criterion
7) Numerical design of a technological evaluator: focusing on the steps
8) Study of the adhesive film behavior: experiments (peel test)/numerical strategy (peel test)/failure criterion
9) Numerical design of a technological evaluator: in house mixed failure criterion
10) Numerical modelling: how to proceed for multi-step repairs ?
11) Adaptation of the light model to the multi-step repairs/ experimental validation
12) Goals and intents/get a desired stress state at the desired localization
13) Multi axial testing machine: capabilities/SOW of the technological evaluator
14) Numerical design of a technological evaluator: specifications/focusing on the steps/modelling of the testing machine/failure criteria
15) Results of the design of the kinematic/numerical design
16) Manufacturing/repair patch lay-up and machining of the evaluators/Abrasive Water Jet
17) Evaluator test
18) Post mortem tomographic analysis
19) Conclusion and prospects

1) Development of light usable numerical models for industry



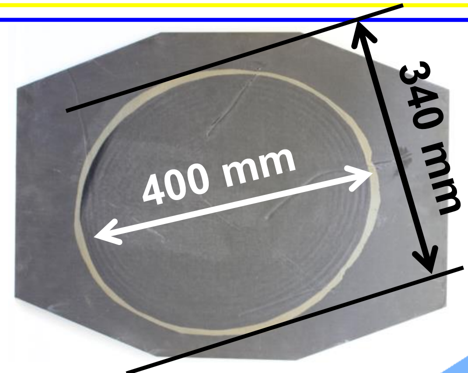
2) Goals and intents: development of generic methods for repair

- From the scientific point of view: most of the literature focuses on small-sized coupons → variabilities of the structure and edge effects non taken into account → **Studies non representative of the "reality".**

- Need to work at upper scales → the **M**ulti **I**nstrumented **T**echnological **E**valuator:
  - several tens of centimeters length and width,
  - designed case by case,
  - representative of the issues in an industrial primary composite structure.

- **Intents of the work**:
  - evaluate the behavior of **the interface area of a step-lap** repaired evaluator studying the debonding of the assembly zone in a representative manner,
  - **development of generic methods of repair analysis usable in industry and for the certification evolution.**

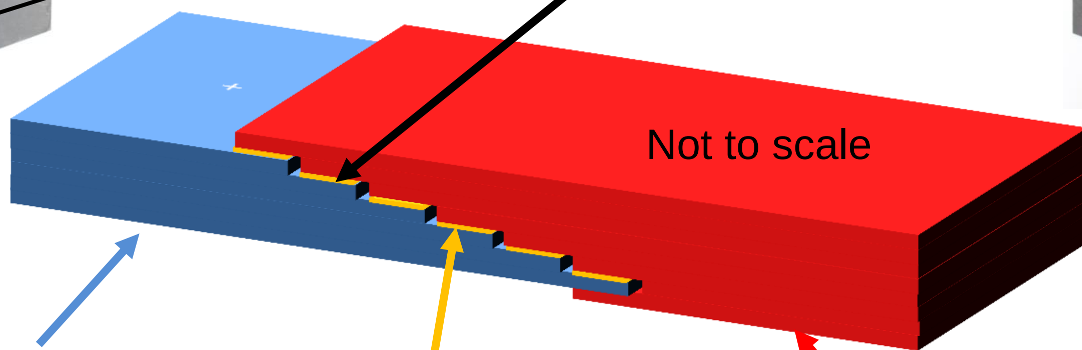
2) Goals and intents: problem statement



Dimensions: **600 mm x 450 mm**

Evaluator front side with the patch

Step-lap shape for interface



Evaluator reverse side: through repair

Damaged composite part

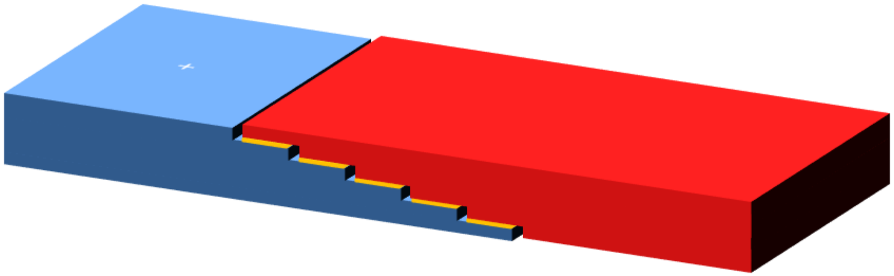
Adhesive film

Composite repair patch

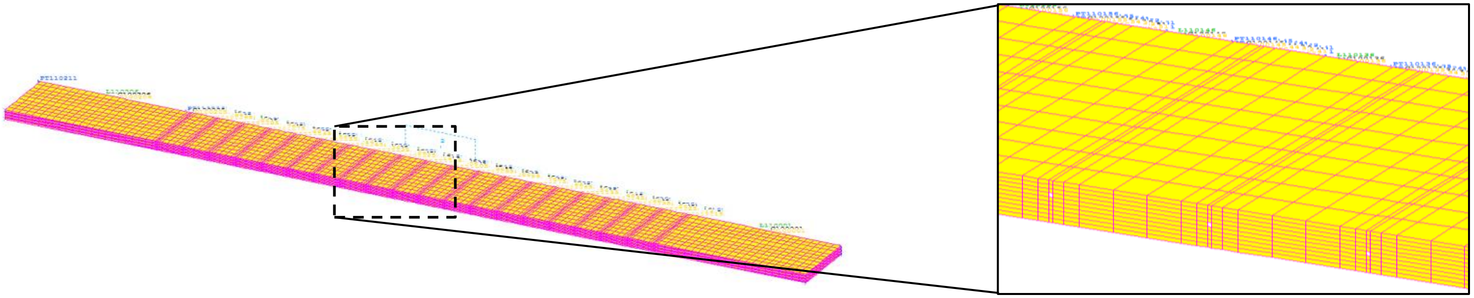
Three challenges with interactions between them:

- numerical strategies suitable for step lap bonded repairs ;
- mechanical characterization of step lap bonded repairs within severe and representative solicitations ;
- evaluation of the repair process robustness.

2) Goals and intents:
Numerical issues for step lap repair



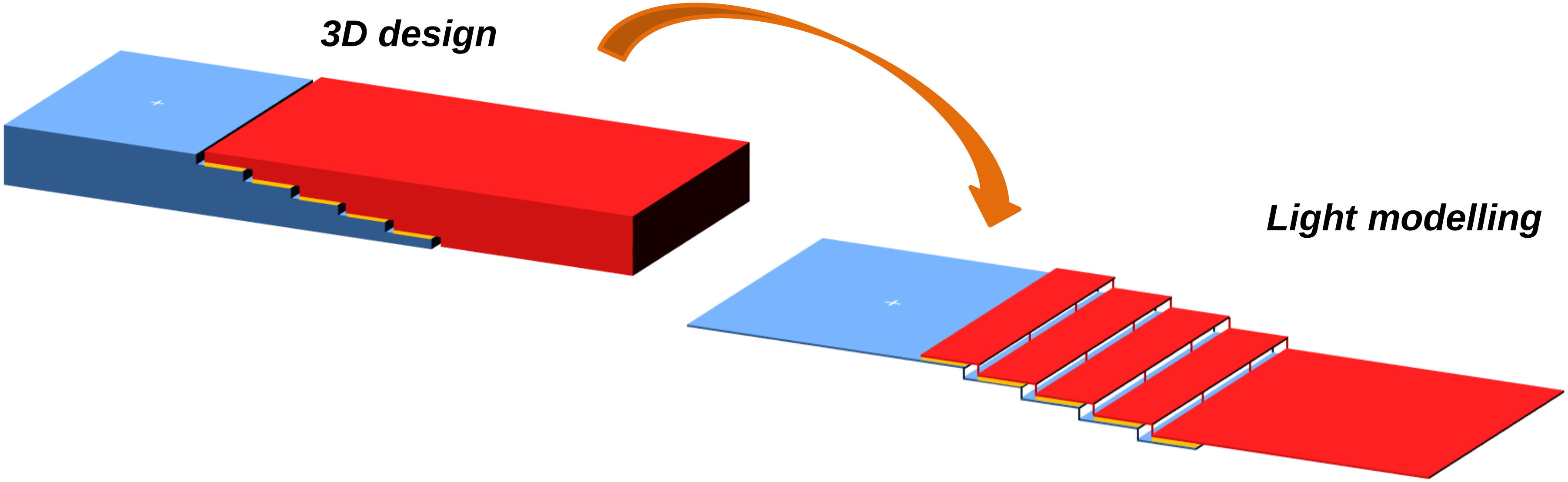
Classical numerical modelling for this type of shape with one step by ply!:
- one volume finite element or more on the thickness for each step (one finite element per ply if the height step is the ply thickness),
- cohesive elements to asses stresses through the adhesive film.



Main issue:
to evaluate large repairs applied to thick primary components to do not lead **to very heavy numerical models**.

3) Study of the adhesive film behavior: to a light numerical modelling

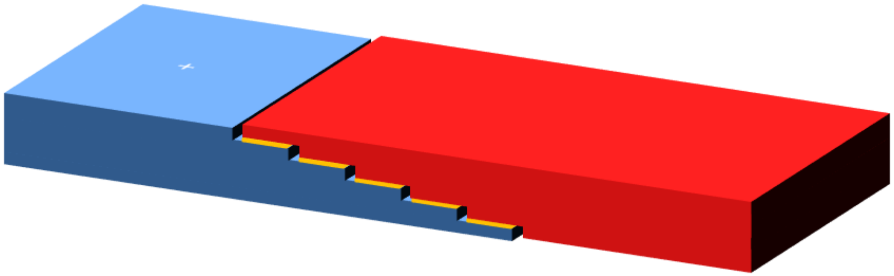
- Implementation of a « **light** » and robust numerical modelling strategy;
- Validate a mixed failure criterion chosen from the literature and fed with the experimental data



To decrease the 3D finite elements number

3) Study on the adhesive film behavior: numerical modelling strategy

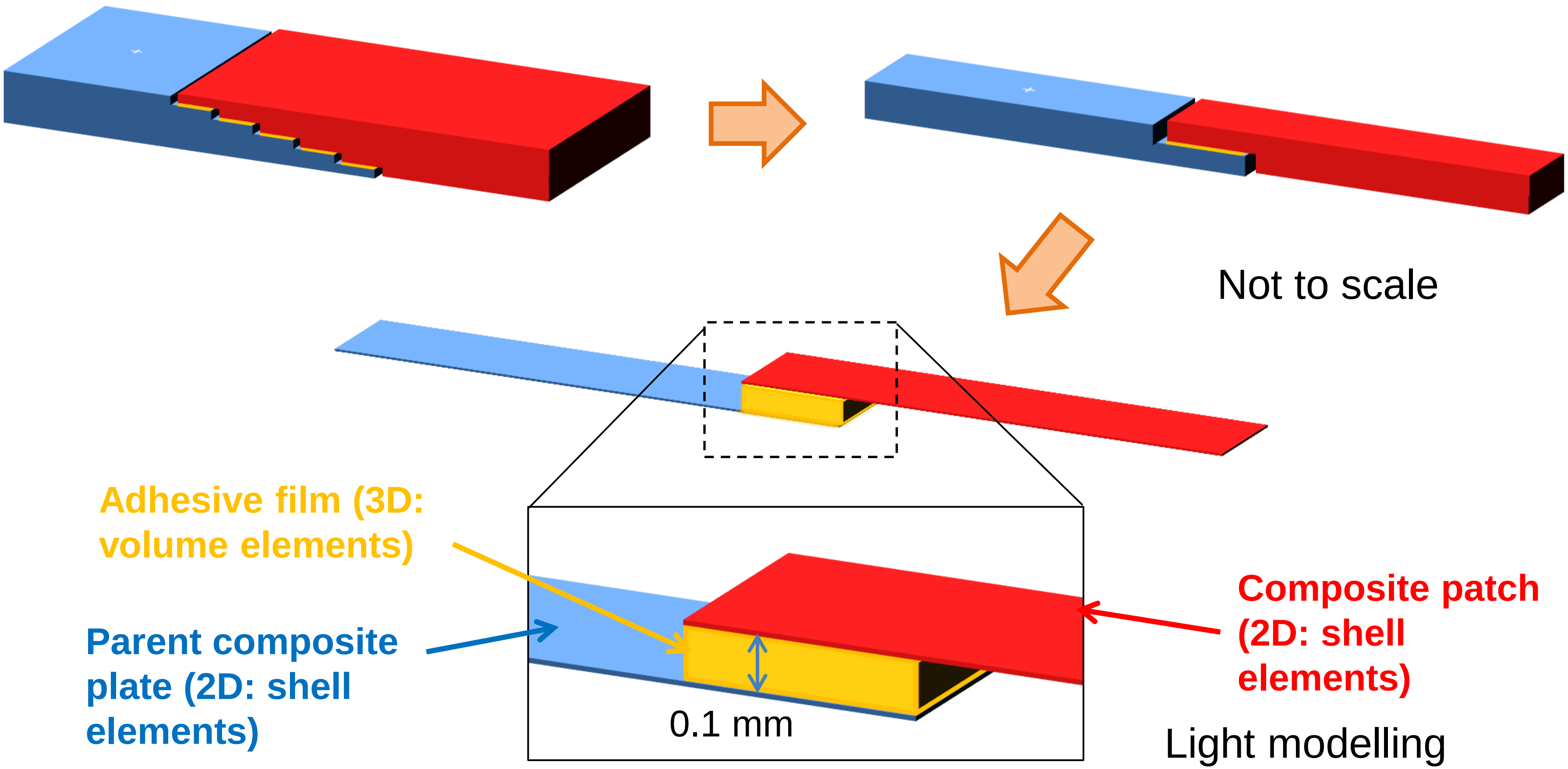
- **To be modelled**:
  - the parent composite plate and the composite patch,
  - the adhesive film.



- **Targeted information**:
  - parent composite plate: in plane stress information = 2D with shell elements (here with Tsai Hill criterion),
  - adhesive film: in plane and out of plane stress information = 3D with volume elements.

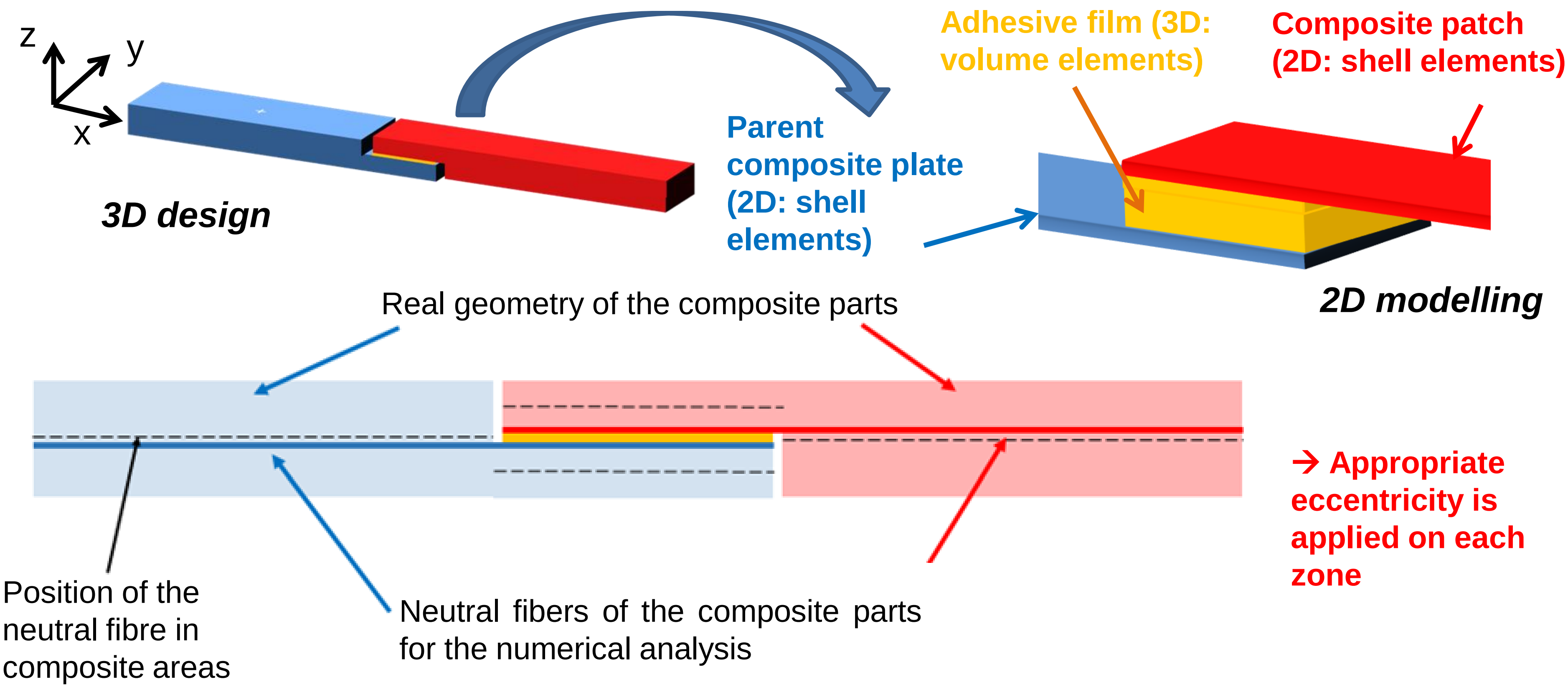
4) Numerical modelling for composite step lap repair evaluation: one-step shape

First stage: **one-step shape**

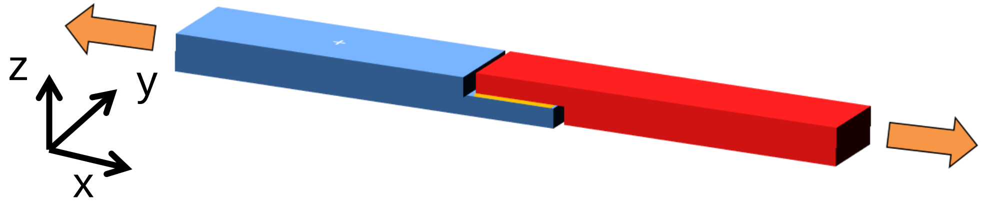


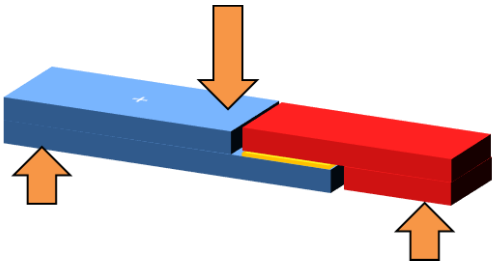
4) Numerical modelling for composite step lap repair evaluation: one-step shape

- Phases of the modelling strategy:
  - the adhesive film is placed in its real localization,
  - the two composite parts are modelled on both sides of the adhesive.



5) Studies on coupons: validate a light modelling strategy

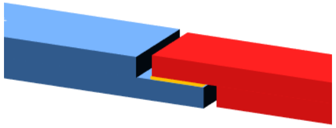




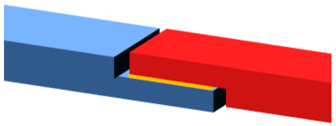
- **Studies on coupons under different load types:**
  - validate a **light modelling strategy** useful for the numerical design of the technological evaluator ;
  - identify the **orders of magnitude** of local values of adhesive film failure in representative manufacturing conditions ;
  - select a mixed **failure criterion** (shear/peel) adapted to the light modelling for our FE choices.

$L_{nominal}$: 12 mm, L_{real}:9 mm 1/30 for 0.3 thickness ply

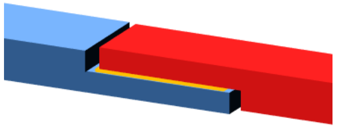
- Different step lengths:



6 mm



$L_{nominal}$: 12 mm

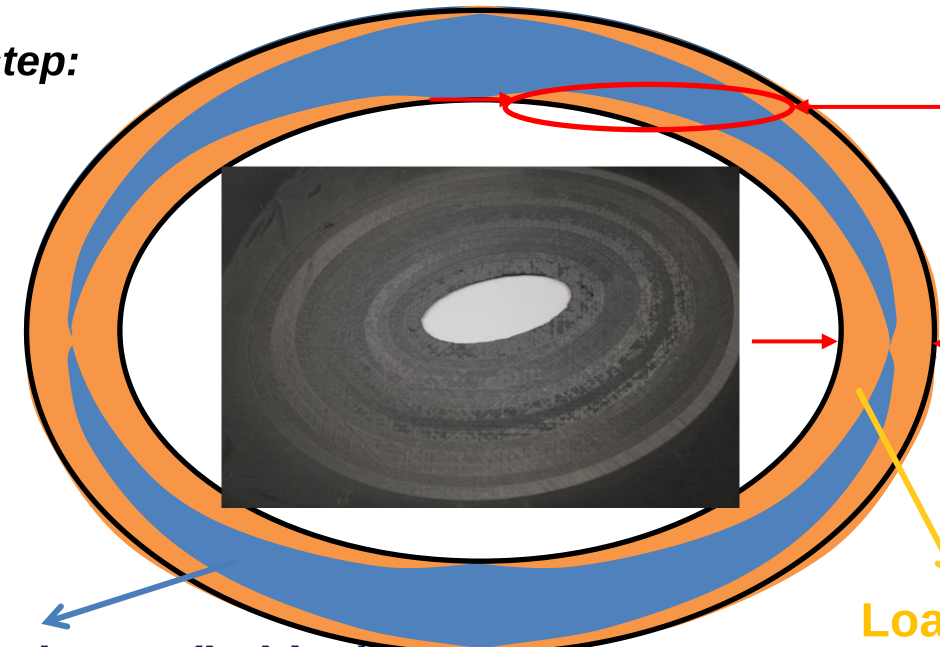


20 mm

6) Study of the adhesive film behavior

3 step lengths: **12 mm** (used in cosmetic repair in SRM A330), **6 mm** and **20 mm** (chosen arbitrarily to embrace the « usual » length values),
→ To have a failure criterion adapted to a large range of step lengths

Elliptic step:



L_{bonding} in the direction of the solicitation >> L_{nominal} of the step

L_{nominal} of the step

Direction of the solicitation

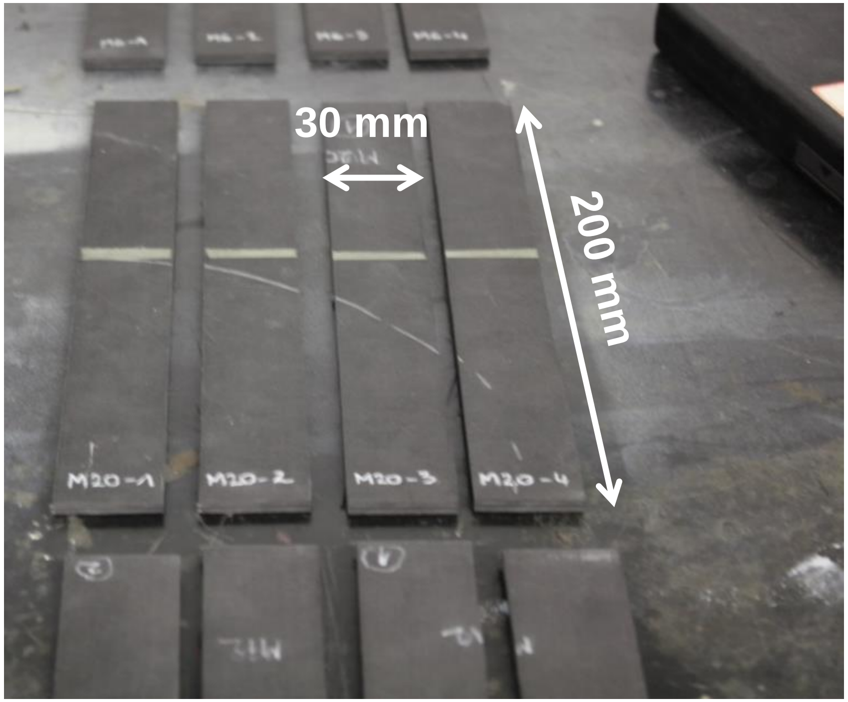
Loaded zone (in orange)

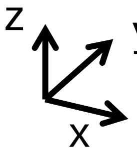
Unloaded zone (in blue)

→ The **criterion must not overestimate** the loading capacity of the **bonded interface** in the area where **the bonding length is way above the nominal length of the step L_{nominal}**

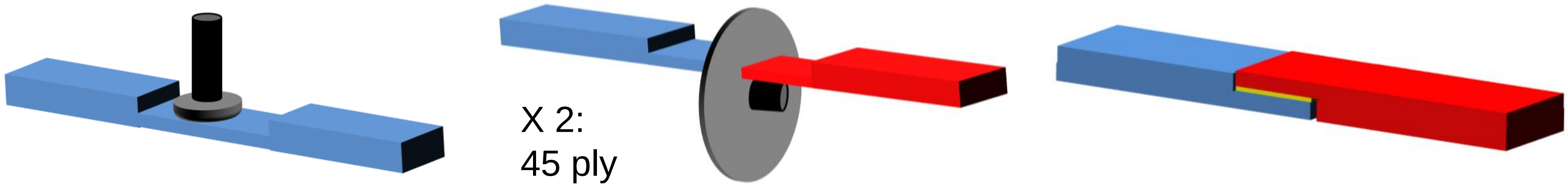
6) Study of the adhesive film behavior: experiments

- Thickness representative of a **reinforced fuselage skin** (4.2 mm): 16 plies HexPly® UD M10 CHS (no aeronautical material)
- **Quasi-iso** stacking sequence: $[0/45/90/-45/-45/90/45/0]_s$
- The **double mirror symmetry** enables the material to be machined **avoiding residual strains release** and turned over to create the step



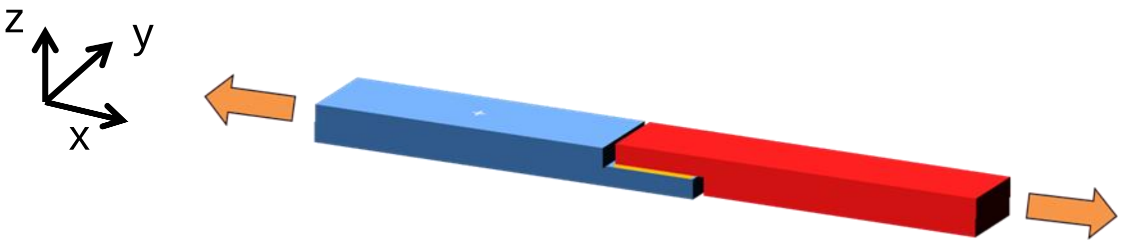


The step: till the middle thickness more half of the adhesive



6) Study of the adhesive film behavior: experiments (shear test)

- **Shear tests → shear stress** solicitations (thanks to a classical formula σ_{xz}=F/S)



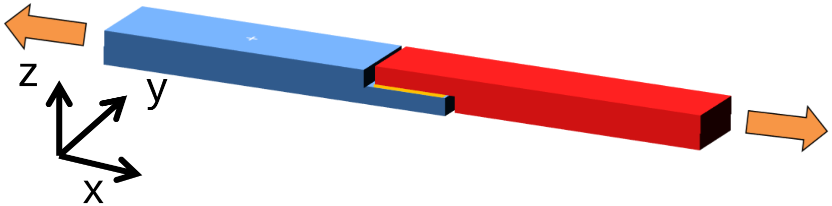
Nominal step length (mm)	6	12	20
Mean real effective bonding length (mm)	3.6	8	14.9
Mean failure load (N)	4180	9018	8680
Mean failure shear stress (MPa)	39	37.9	19.4

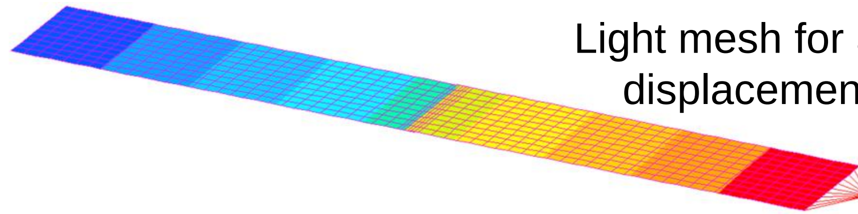
- Similar mean stresses for the two first step lengths but not for 20 mm step length

A criterion based on the mean shear stress values is not reliable

6) Study of the adhesive film behavior: numerical modelling strategy (shear test)

Stress σ_{xz} (MPa) for the failure load with the light modelling





Light mesh for axial displacements

Originality: shear test strategy, not the values

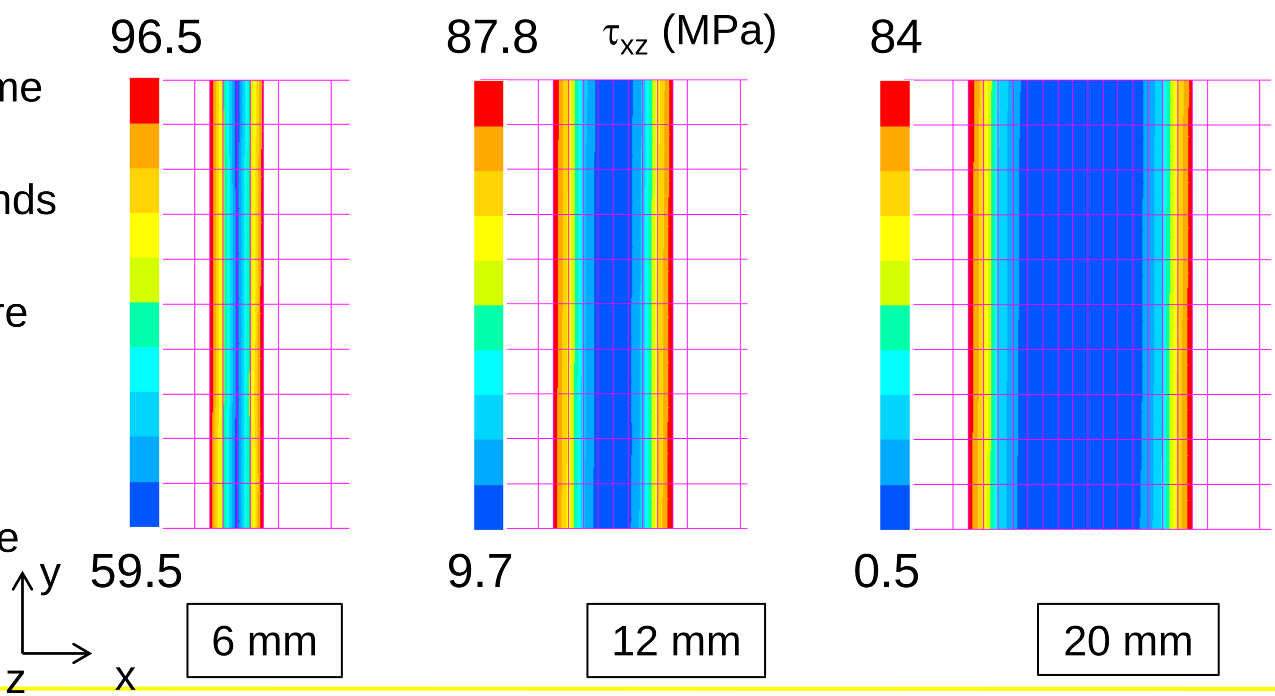
Cartography:

- The evolution of the shear stress seems to be the same for every step length,

→ **Peak of stresses** at the ends of the bonded interface,

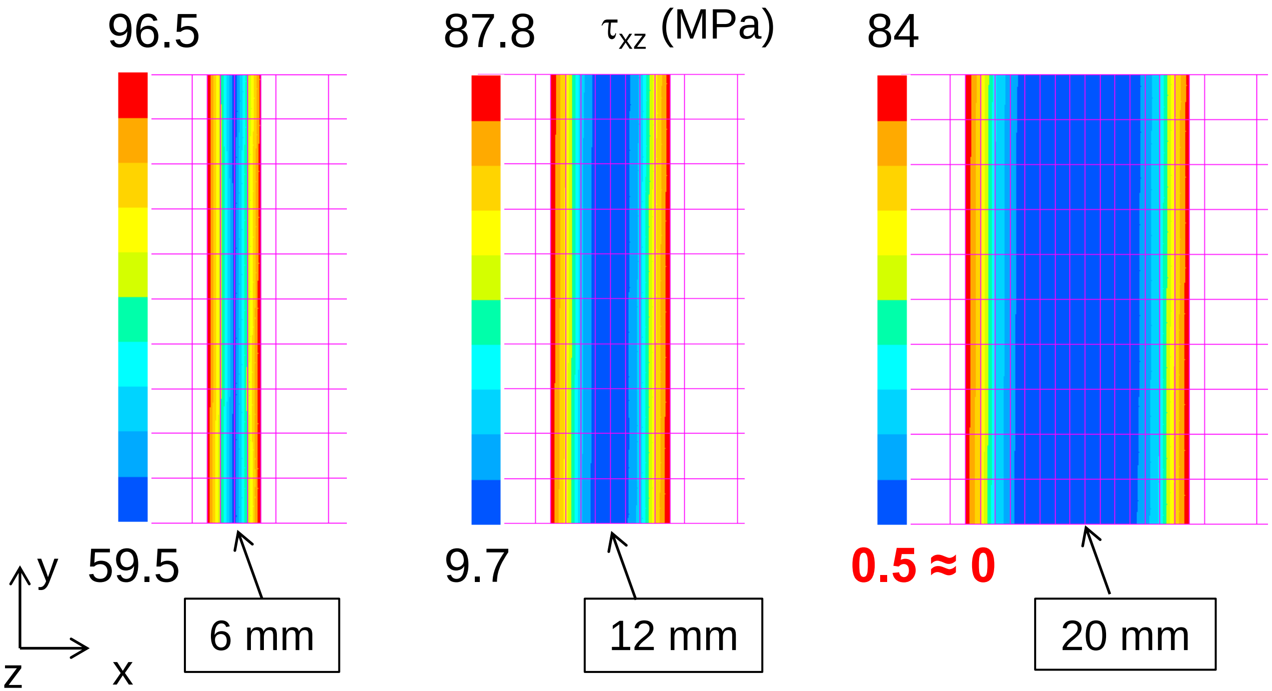
→ Same peaks in the literature for 3D modelling.

- A **slightly loaded area** appears at the centre of the biggest step length.



6) Study of the adhesive film behavior: in house failure criterion (shear test)

• Failure criterion → Feed the numerical model with a **shear failure indicator,**
• Maximum shear stress values are not a good **indicator** (bonding length dependence) **:**



• Existence of **a plateau where the shear stress is non existent (“unloaded zone”)** for a nominal step length of 20 mm → Mean stress values are not representative

6) Study of the adhesive film behavior: in house failure criterion (shear test)

$$\bar{\tau}_{ZX} = \frac{1}{d_0}\int_0^{d_0} \tau_{ZX}\,dx$$

used by Whitney & Nuismer, with d_0: characteristic length, (the bonded length for a scarf lap repair)

Whitney, J.M. & Nuismer, R.J., Stress fracture criteria for laminated composites containing stress concentrations, *Journal of Composite Materials*, 18 (1974) 263-5.

The step length as a characteristic length is an issue because of the “unloaded zone”

→ need to **adapt the criterion** to our case,

→ definition of a **useful length d_u**, equal to the step length (if less than 9.5 mm) and 9.5 mm further

l_i: length of an element i

	Whitney & Nuismer			In house Failure Criterion		
Number of elements	20			20		
Step nominal length (mm)	6	12	20	6	12	20
Size of an element (mm)	0.2	0.41	0.74	0.2	0.41	0.74
Associated criterion (MPa)	40.9	41.3	26.6	40.9	41.3	38.1

$$\bar{\tau}_{ZX} = \frac{1}{d_u}\sum \tau_{ZX\,i} \times l_i$$

In house shear criterion

The **useful length** enables us to find **shear stress values** that are similar for every step length

7) Numerical design of a technological evaluator: focusing on the steps (shear test)

Goal: to have the **lightest model** while being **robust and reliable**

20 mm bonding length

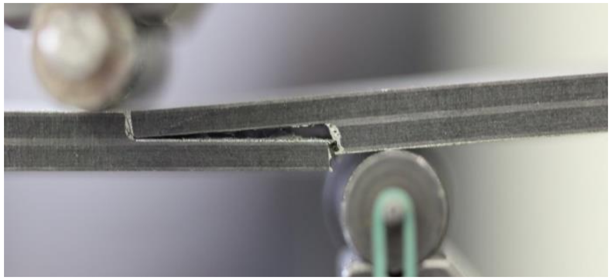
Number of elements: in the adhesive (without the gap)	2	3	4	6	8	10	12
Size of the element (mm)	7.63	5.08	3.81	2.54	1.9	1.53	1.27
Shear stresses (MPa) calculated by our criterion	32.2	41.5	41.5	41.9	41.4	40.7	40.1

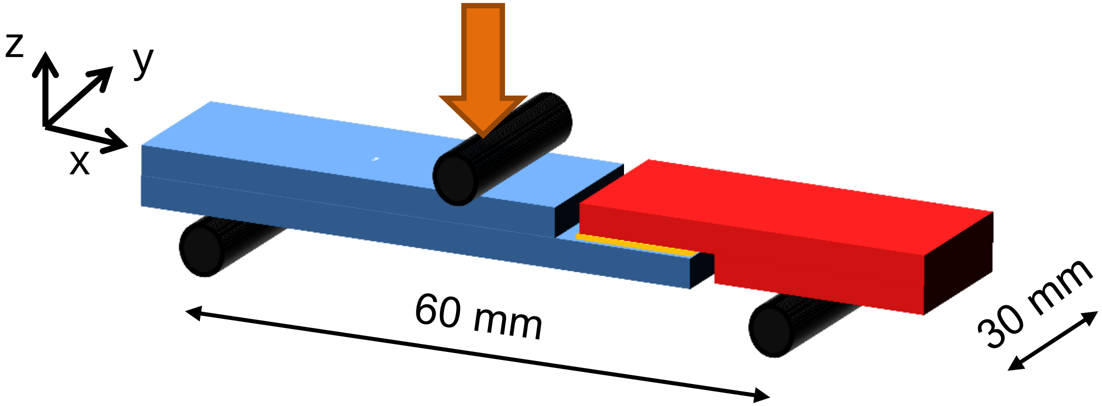
- **5 finite elements in the step length (including 1 for the gap)**

→ **Minimum number in order to have reliable information on the stresses in the steps**

8) Study of the adhesive film behavior: experiments (peel test)

- **Peel tests → peel stress** solicitations (thanks to a classical formula σ_{zz}=F/S)

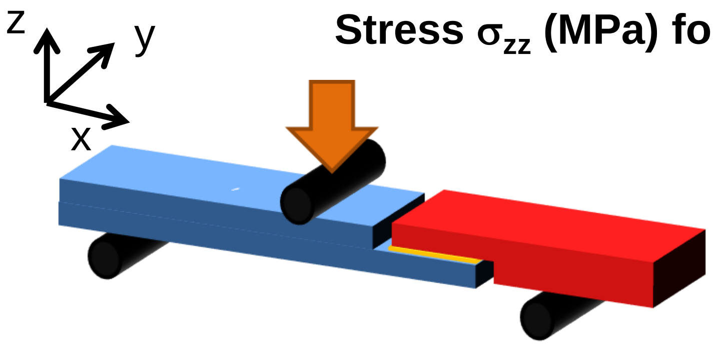




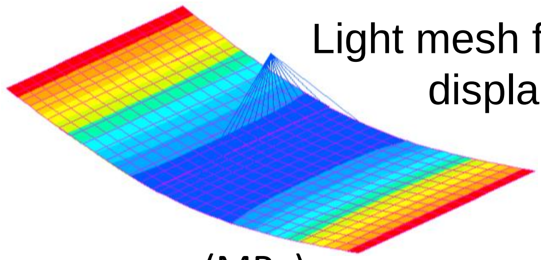
Nominal step length (mm)	6	12	20
Mean real effective bonding length (mm)	3.6	8.0	14.9
Mean failure load (N)	709	1297	1725
Mean failure peel stress (MPa)	6.6	5.5	3.9

Mean peel stress indicator not usable

8) Study of the adhesive film behavior: numerical modelling strategy (peel test)



Stress σ_{zz} (MPa) for the failure load with the light modelling

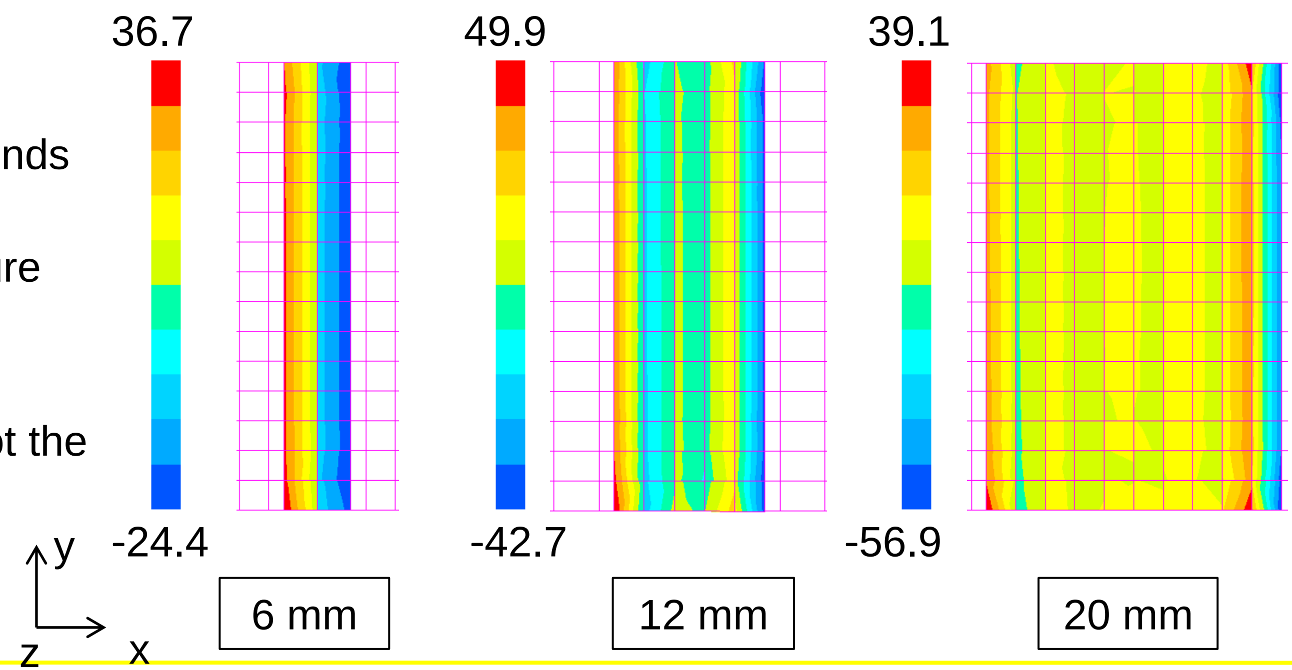


Cartography:

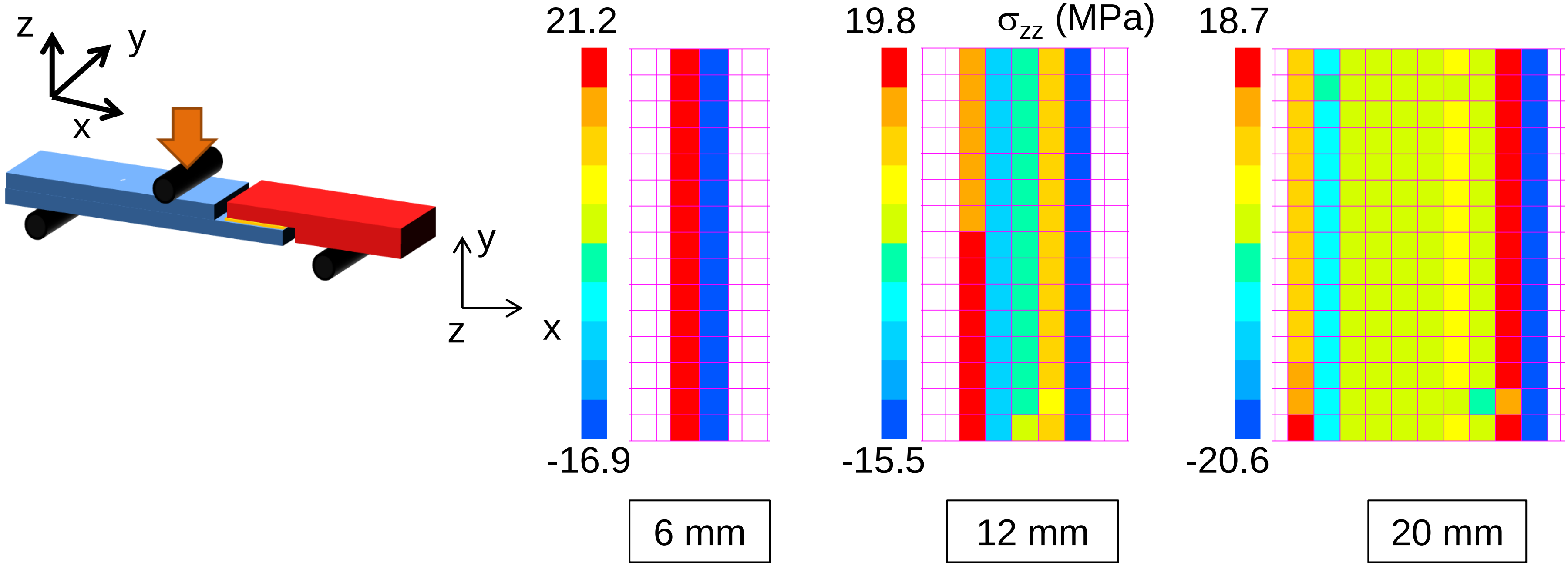
→ **Peak of stresses** at the ends of the bonded interface,

→ Same peaks in the literature for 3D modelling.

Local maximum values are not the same



8) Study of the adhesive film behavior: in house failure criterion (peel test)



- To be homogeneous with the strategy defined in shear, it was decided to work in average stress by element ;
- The best compromise: length of elements about 2 mm ;
- The maximal value of the positive part of peel stresses under these conditions is about 20 MPa.

9) Numerical design of a technological evaluator: in house mixed failure criterion

• Mixed failure criterion which would be common for any step length

$$\left(\frac{\bar{\tau}_{XY}}{R_a}\right)^2 + \left(\frac{\bar{\sigma}_{ZZ}}{S_a}\right)^2 \leq 1$$

→ used by:

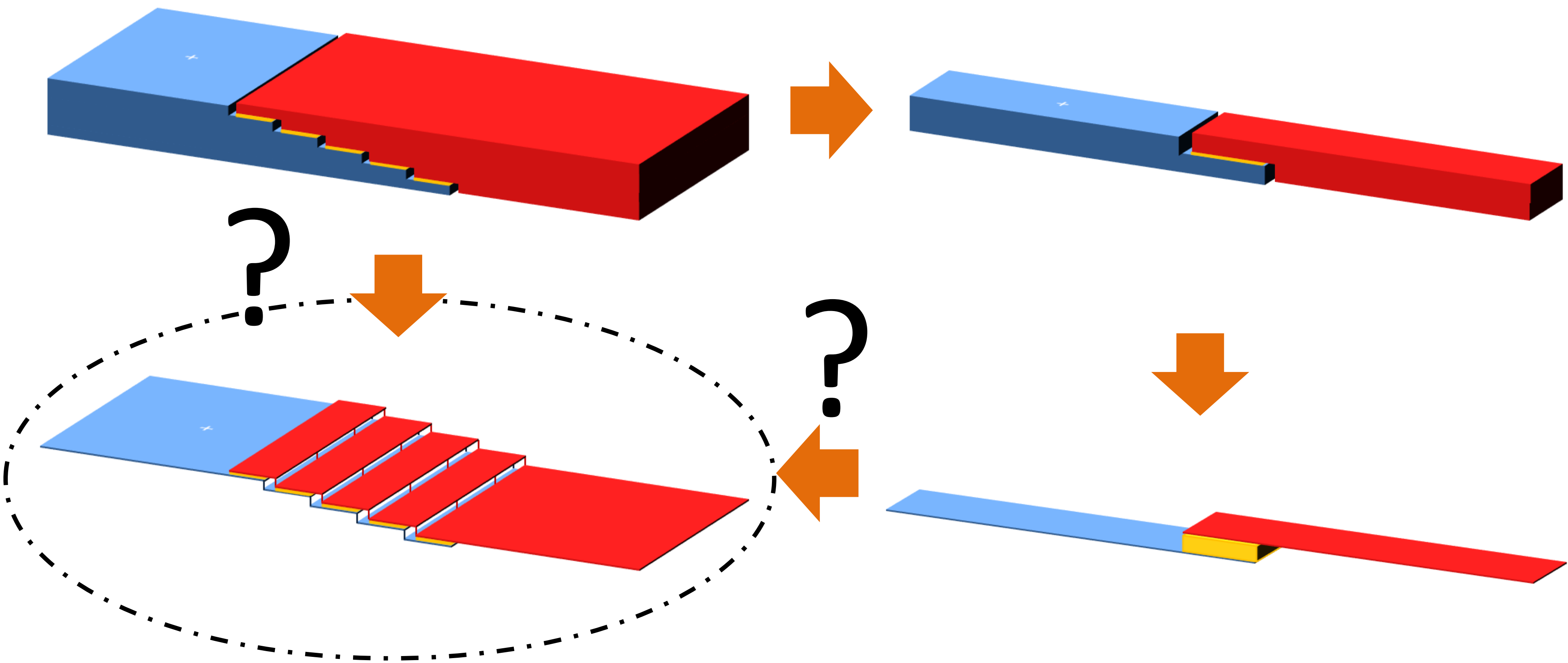
[Cognard, 2011]: Cognard, J.Y., L. Sohier, and P. Davies.
"A Modified Arcan Test to Analyze the Behavior of Composites and Their Assemblies Under Out-of-plane Loadings", *Composites Part A: Applied Science and Manufacturing,* 42.1 (2011): 111–121.

Based on the previous assumptions up to the step ratio of 30 (step length of 9 mm):

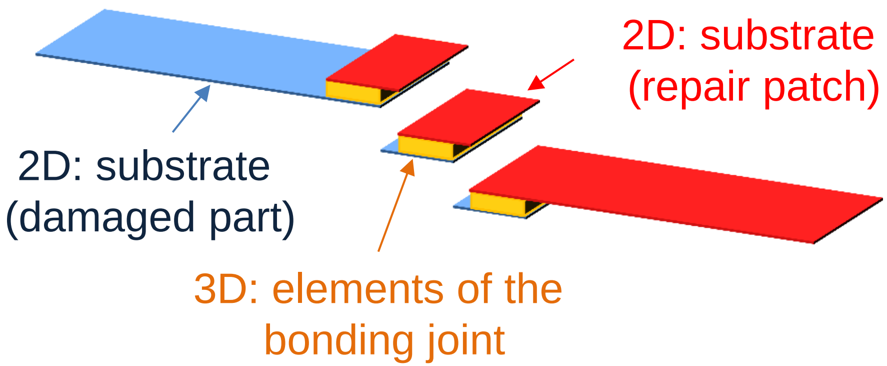
- R_a= Ultimate shear stress = 40 MPa,
- S_a= Ultimate peel stress = 20 MPa.

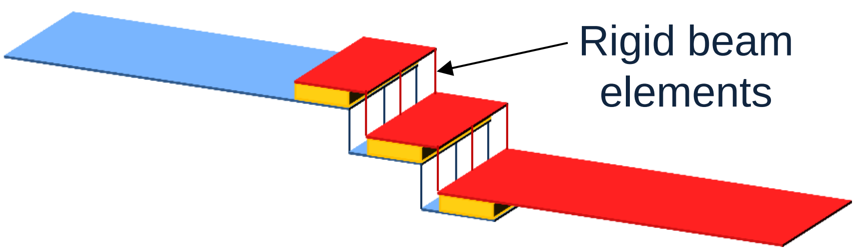
→ Values found in our case of study, with our type of repair and our experimental conditions

10) Numerical modelling: how to proceed for multi-step repairs ?



11) Adaptation of the light model to the multi-step repairs





Adhesive film modelled by volume elements placed at its real position ;

Composite substrates modelled by 2D: shells placed directly in contact with the adhesive ;

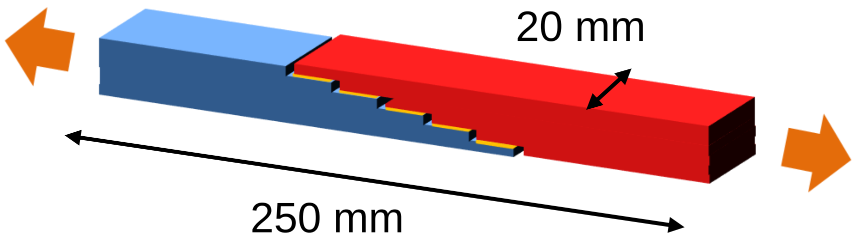
Issue: composite substrates are modelled by several non-adjacent planes ;

Solution: linking of the substrate planes node by node (all the damaged part planes together and all the repair patch planes together) by the use of rigid beam elements ;

Associated nodes constrained in their displacements and rotations ;

As a last phase, the "real" position of the neutral fiber is imposed.

11) Adaptation of the light model to the multi-step repairs: experimental validation

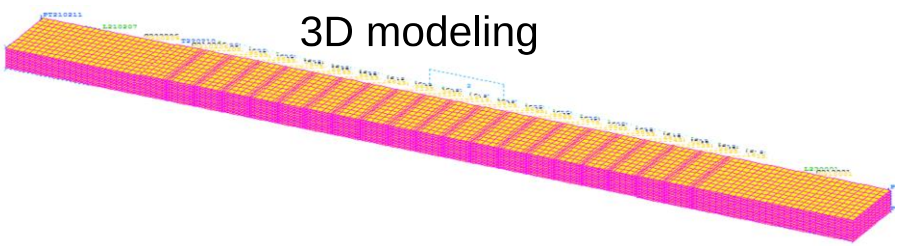


Thickness representative of a **reinforced fuselage skin** (5.0 mm) →20 plies HexPly® UD T700M21 GC

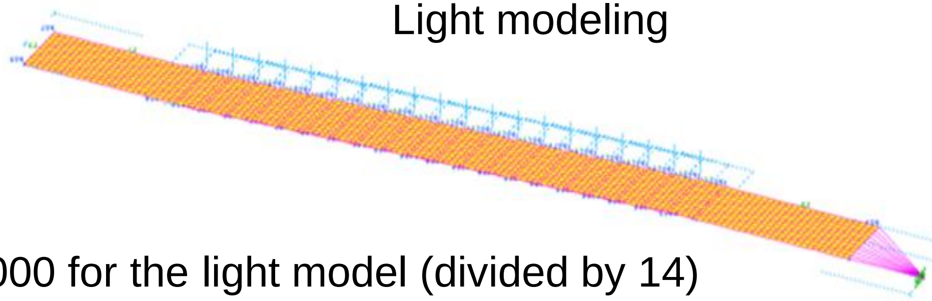
Stacking sequence **strongly oriented**: $[0/45/0/-45/0/90/45/0/-45/0]_s$

20 steps milled with Abrasive Water Jet process

Experimental mean failure load at 80 kN with debonding of the interface



3D modeling



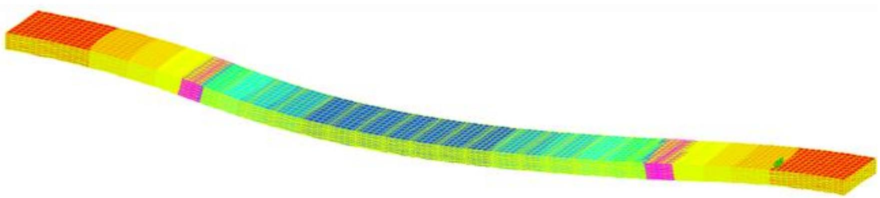
Light modeling

Number of D.o.F: 550000 for the 3D model vs 40000 for the light model (divided by 14)

CPU Time Saving: over 3 minutes for the 3D model vs 16 seconds for the light model (divided by 12)

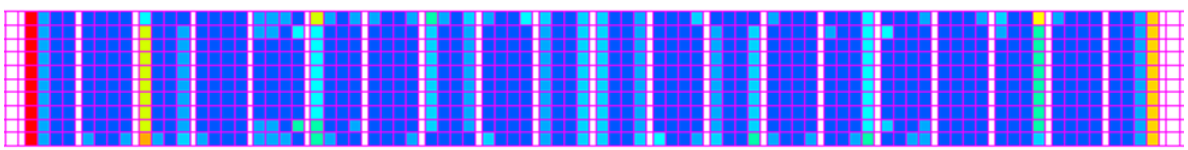
11) Adaptation of the light model to the multi-step repairs: experimental validation

Out of plane displacements (mm)



at failure load for 3D model

at failure load for light model



Prediction of bonding failure using the in-house mixed-mode criterion at experimental failure load

$$\left(\frac{\overline{\tau}_{XY}}{R_a}\right)^2 + \left(\frac{\overline{\sigma}_{ZZ}}{S_a}\right)^2 \leq 1$$

→ Feasibility of the 2D modelling for a large sized evaluator

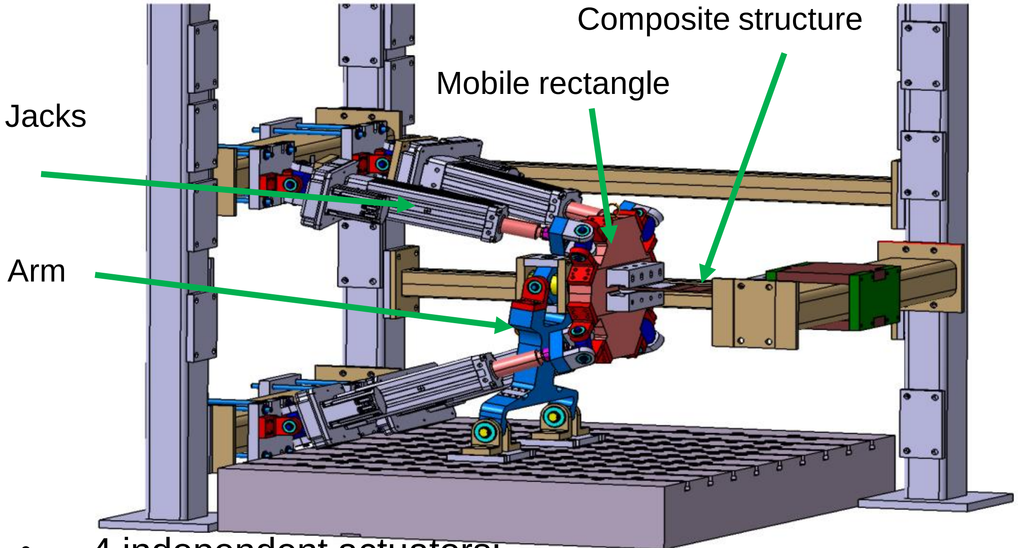
12) Goals and intents: development of generic methods for repair

- From the scientific point of view: most of the literature focuses on small-sized coupons → variabilities of the structure and edge effects non taken into account → **Studies non representative of the "reality".**

- Need to work at upper scales → the **M**ulti **I**nstrumented **T**echnological **E**valuator:
  - several tens of centimeters length and width,
  - designed case by case,
  - representative of the issues in an industrial primary composite structure.

- **Intents of the work**:
  - evaluate the behavior of **the interface area of a step-lap** repaired evaluator studying the debonding of the assembly zone in a representative manner,
  - **development of generic methods of repair analysis usable in industry and for the certification evolution.**

12) Goals and intent:
get a desired stress state at the desired localization



- 4 independent actuators:

→ combination of 4 elementary moves (3 rotations and 1 translation)

→ infinity of kinematics

- The numerical design of the evaluator and its kinematics goes through a **iterative numerical process** → kinematic and geometrical parameters are unknown

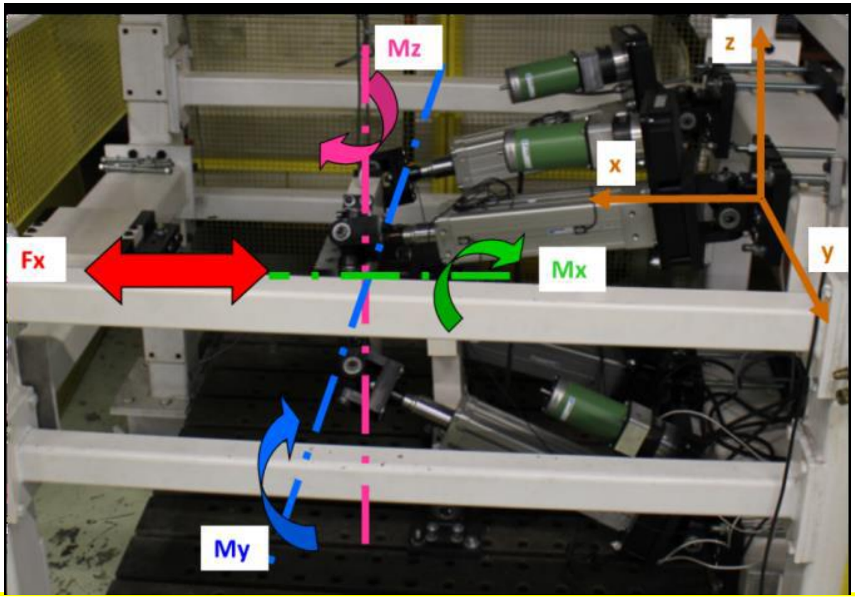
USE of the "LIGHT" MODELLING STRATEGY TO BEAR THE ITERATIONS ON A DETAIL-SIZED EVALUATOR

Composite structure embedded on its ends:

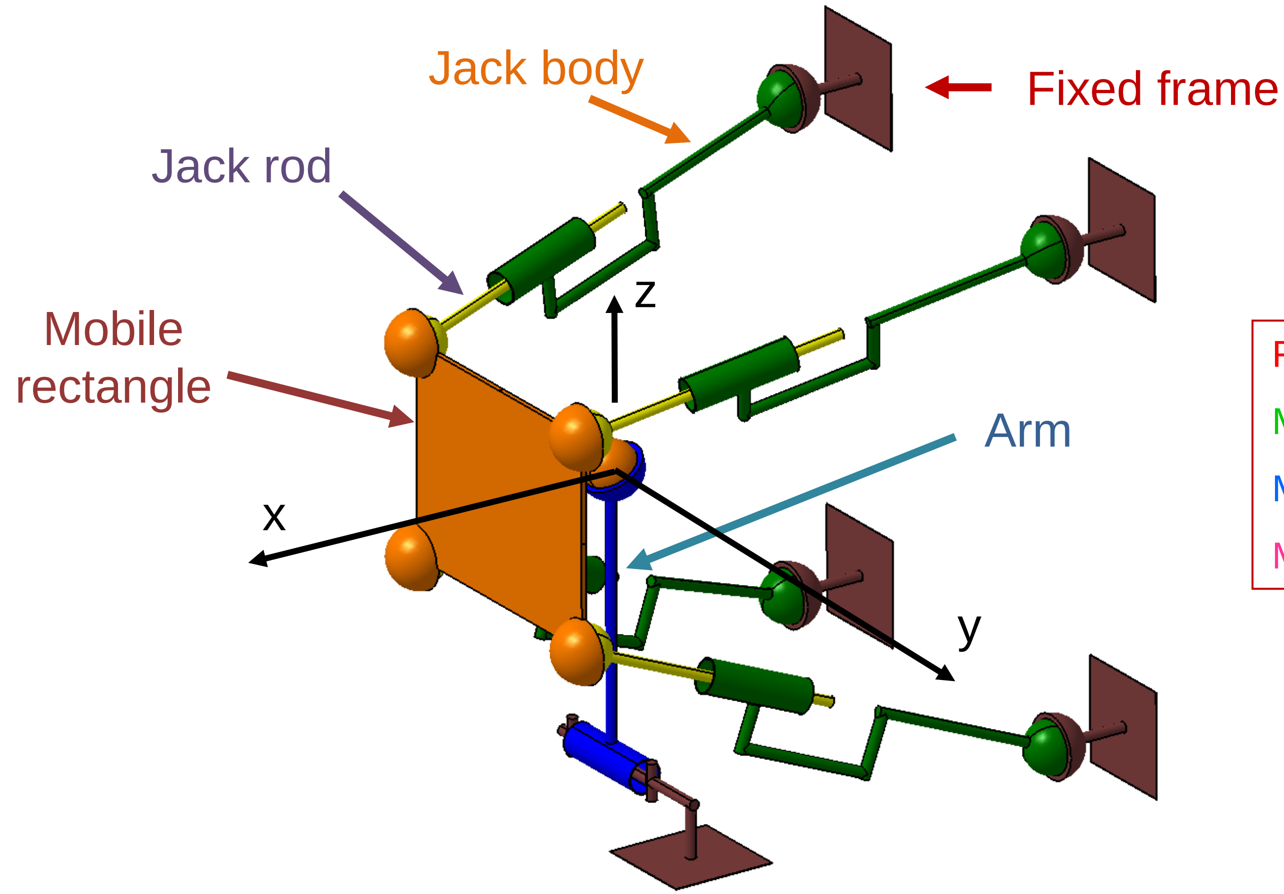
- 1 attached end,
- 1 end fixed to a mobile rectangle.

Position of the actuators rods guided depending on time

- Enable to impose a chosen displacement path in order to direct the deformations



13) Multi axial testing machine: capabilities



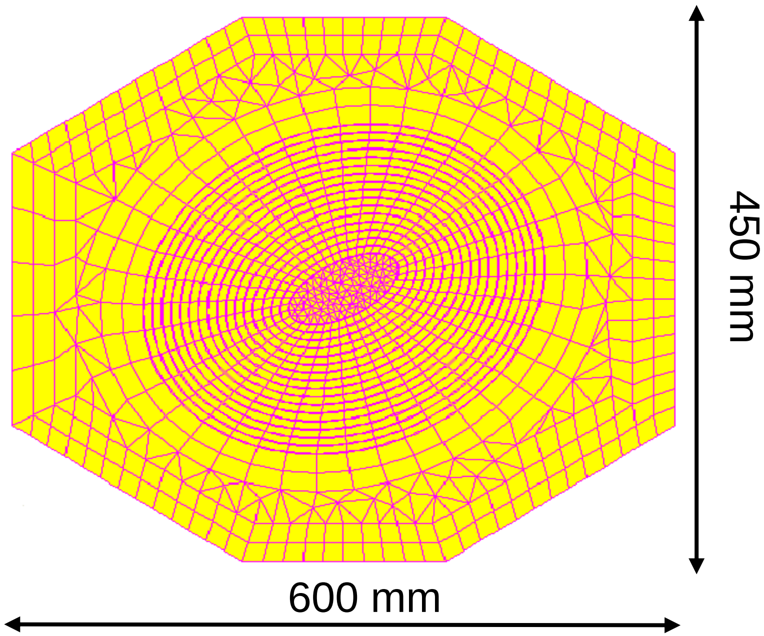
Fx_{max} = 140 kN, Δ = ± 100 mm

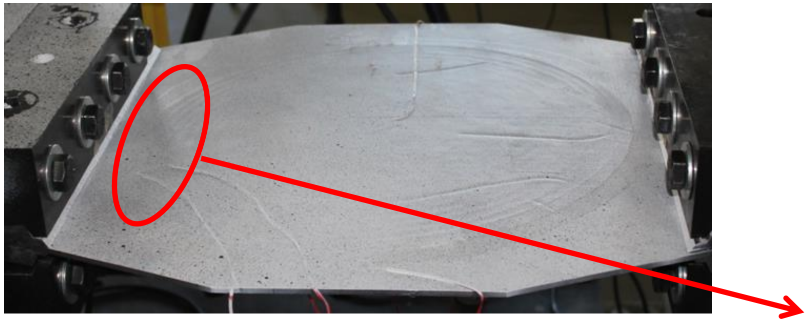
Mx_{max} = 8 kN.m, α_{max} = ± 15°

My_{max} = 30 kN.m, α_{max} = ± 20°

Mz_{max} = 40 kN.m, α_{max} = ± 20°

13) Multi axial testing machine: SOW of technological evaluator





- ***Closed repair**: To avoid edge effects and to be more representative of a "real industrial situation"*
- Thickness representative of a **reinforced fuselage skin** (4.2 mm) → 16 plies HexPly® UD M10 CHS
  Stacking sequence **quasi-iso**:
  $[0/45/90/-45/-45/90/45/0]_s$
- **Elliptic geometry** of the patch: geometry currently used in the literature *[Wang, 2009]*
- step ratio of 1/30 (9 mm length for each step)
- Dimensions: **600 mm x 450 mm to be able to contain the closed repair**

→ Quite important compared to the usual lab coupons

Goal: design a complex kinematics to break the bonding joint under mixed mode in the area of interest

14) Numerical design of a technological evaluator: specifications

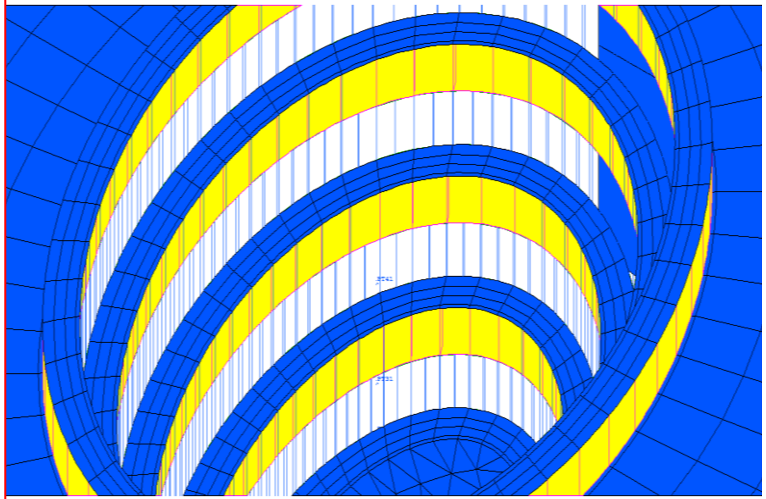
Composite parts = shell composite **2D elements**
Bonded joint = volume **3D elements**

→Information in and out the plane for the adhesive film

→ Information only in plane for the composite parts

Why?:

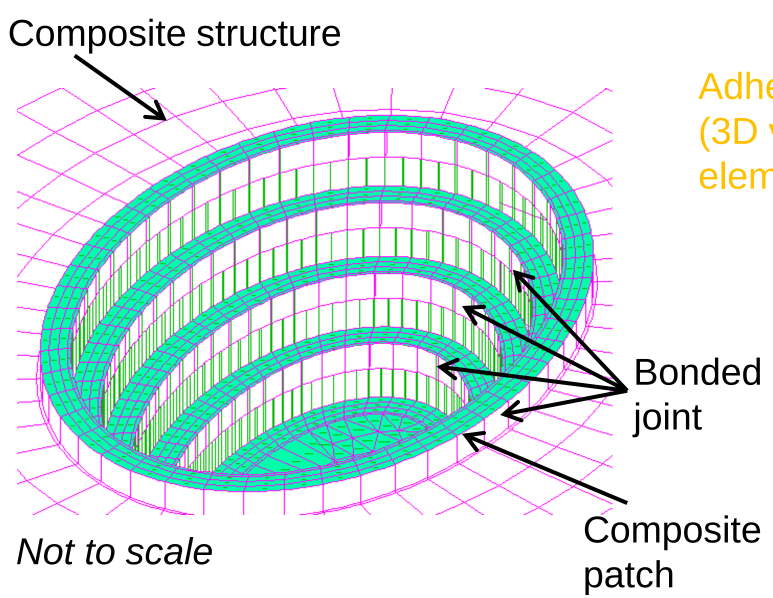
- the **MITE Toolbox** designed to study the behavior of the adhesive film in **shear/peel** (out of plane) stresses,
- the displacement path adapted to concentrate the **solicitations on the bonded interface at a given location**

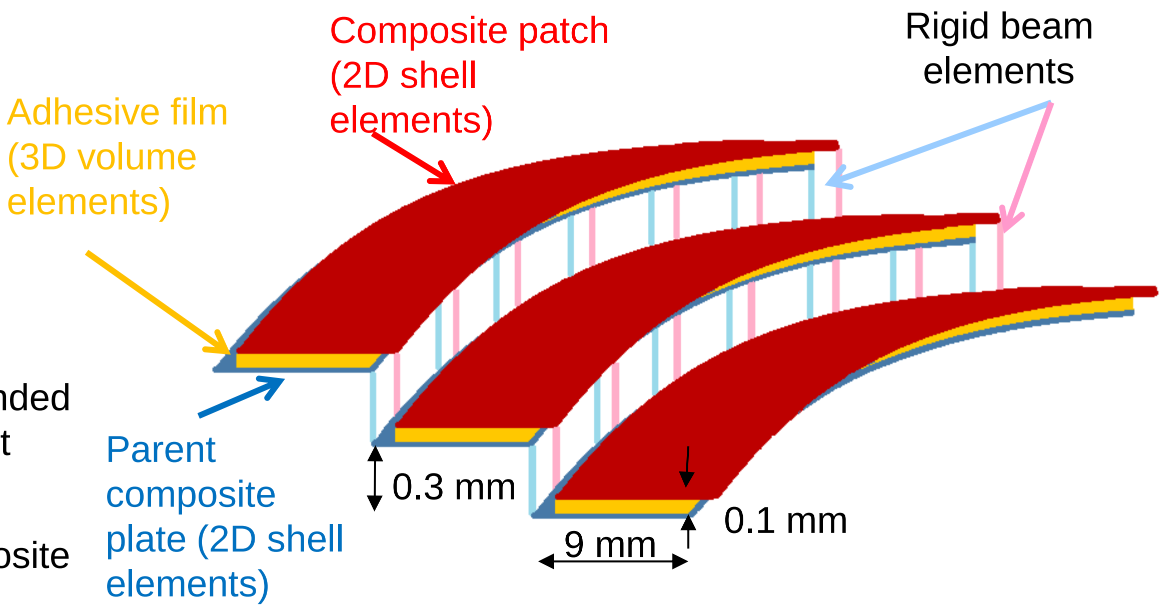


Not to scale

14) Numerical design of a technological evaluator: focusing on the steps

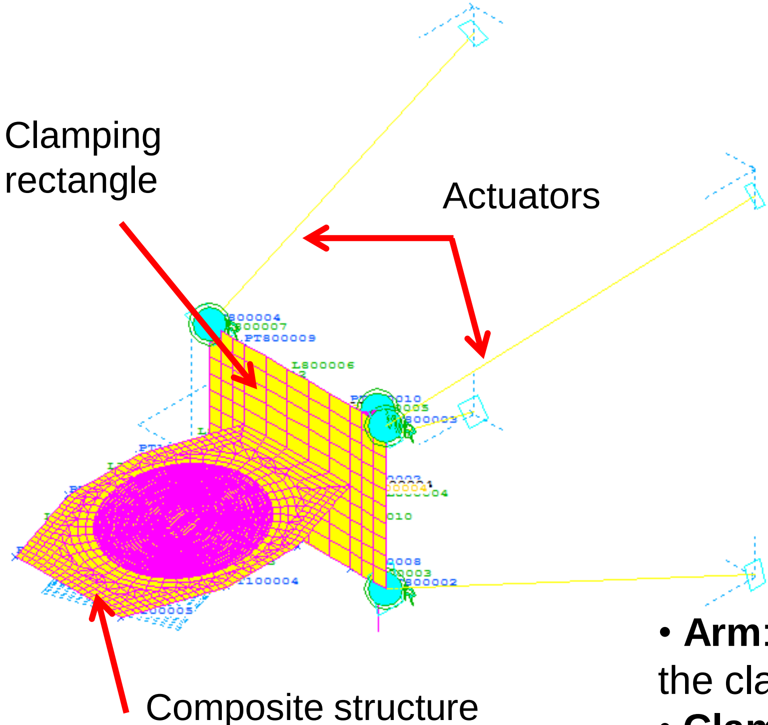
• Step length: 9 mm including 1 mm gap (step ratio of 30 and representation of the variability of the positioning)
• Adhesive film areas designed in their real plane → planes of the composite parts created outside the mean plane of each sub assembly (patch or parent plate)

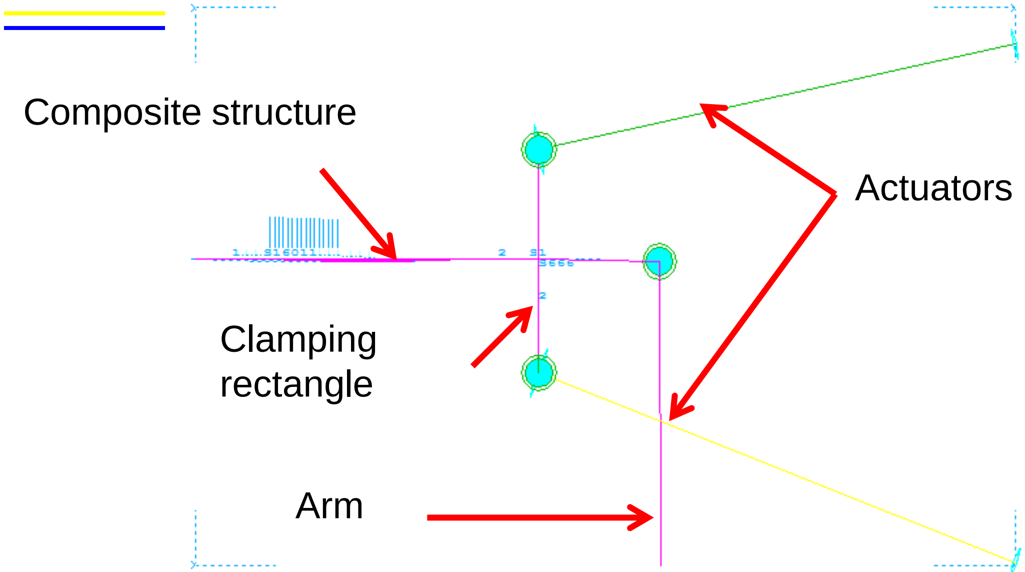




Use of **rigid beam elements**, which link the plane of each composite part altogether:
→ associated nodes constrained in all the directions and rotations.

14) Numerical design of a technological evaluator: modelling of the testing machine





- Number of DOF: 121634
- Total number of elements: 12146

- **Arm**: infinitely rigid part and articulated via a ball joint links with the clamping rectangle,
- **Clamping rectangle**: shell elements with the real thickness and material,
- **Actuators**: slide links connected to the 4 corners of the clamping rectangle and to the fixed assembly via ball joint links

Why the design of the fixed assembly?:
→ Control of the displacements of the jacks and taking into account of the stiffness of the assembly,
→ Control of the respect of the admissible strokes of the actuators and possibilities to know and limit the loading in the jacks under the maximum admissible loading.

14) Numerical design of a technological evaluator: failure criteria

• Condition of the evaluation of the failure → definition of **three groups**, each of them with failure criterion

• **« Failure »** (where the patch debonding is desired) and **"Intact bonding" groups** (where the adhesive film must hold on):
→ Groups submitted to a **in house mixed failure criterion**, combining peel and shear stress ultimate values:

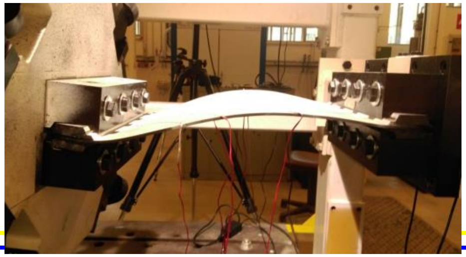
$$\left(\frac{\bar{\tau}_{XY}}{Ra}\right)^2 + \left(\frac{\bar{\sigma}_{ZZ}}{Sa}\right)^2 \leq 1$$

• **« Composite » group** (which must not fail before the patch debonding):
→ Group defining the substrates thanks to a "classical" **Tsai-Hill criterion**:

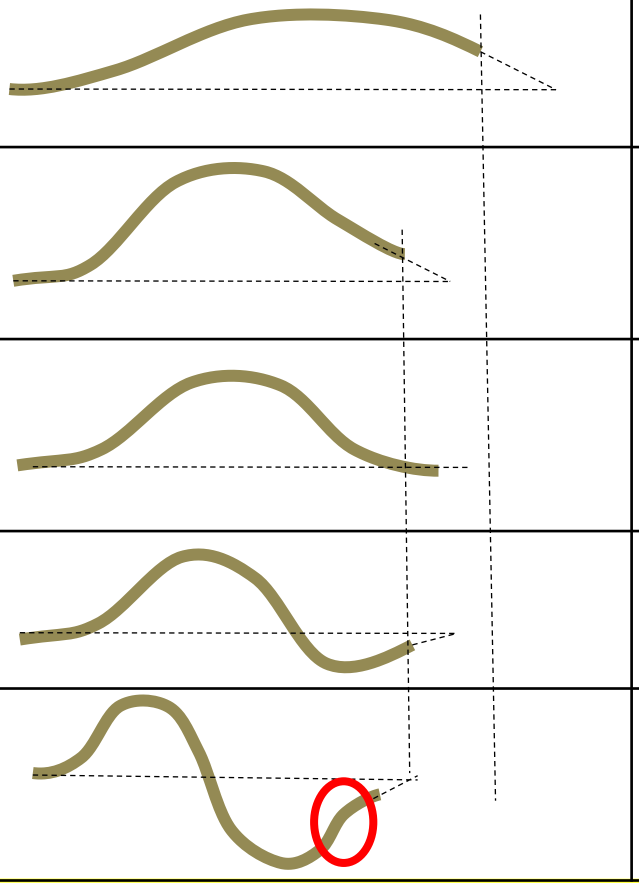
$$\left(\frac{\sigma_{XX}}{X}\right)^2 + \left(\frac{\sigma_{YY}}{Y}\right)^2 - \frac{\sigma_{XX}\sigma_{YY}}{X^2} + \left(\frac{\tau_{XY}}{S}\right)^2 < 1$$

→Those groups enable the implementation of goals and stresses during the optimization process

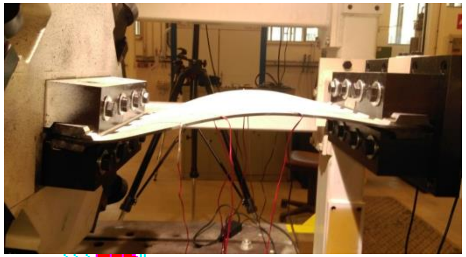
15) Results of the design of the kinematic: after ten iterations



Phases		Alpha (°)	Displa. x (mm) Articulation center
Phase 1: bending + compression		7	4
Phase 2: compression leads to buckling		7	7
Phase 3: bending return to zero		0	5
Phase 4: bending in the opposite direction		-5.7	7
Phase 5: compression to create double-buckling		-5.7	12

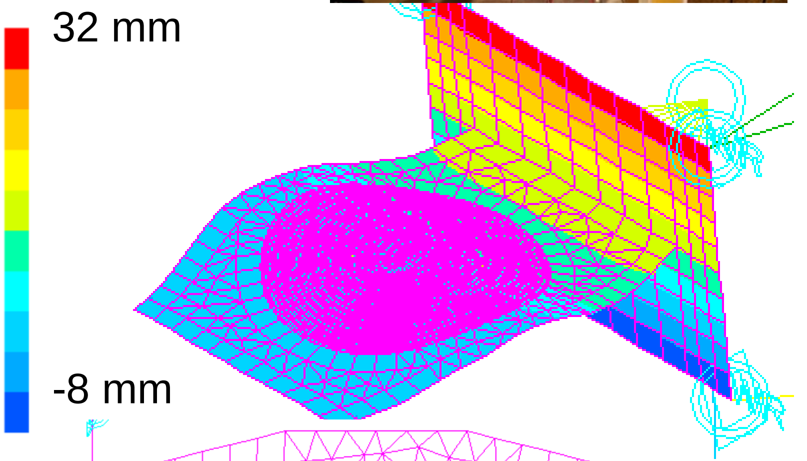


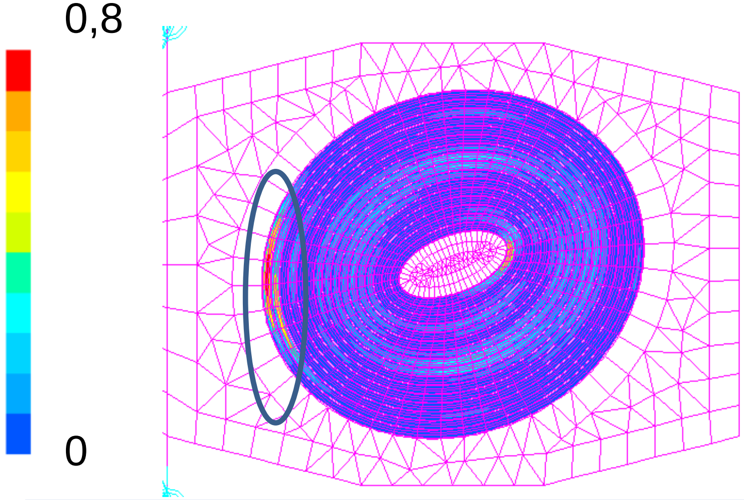
15) Results of the design of the kinematic: numerical calculations



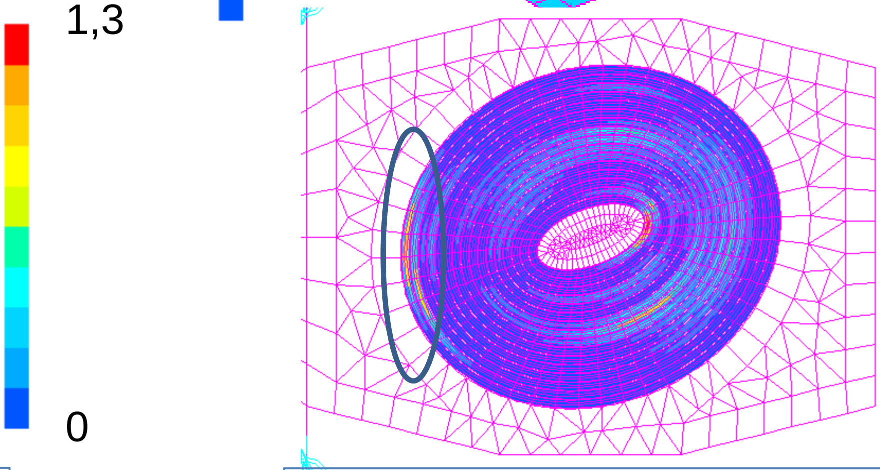
Kinematic with a sequence of compression and flexion to create a double buckling:

In plane displacements along x axis: final stage





End of the phase 4: just before the failure



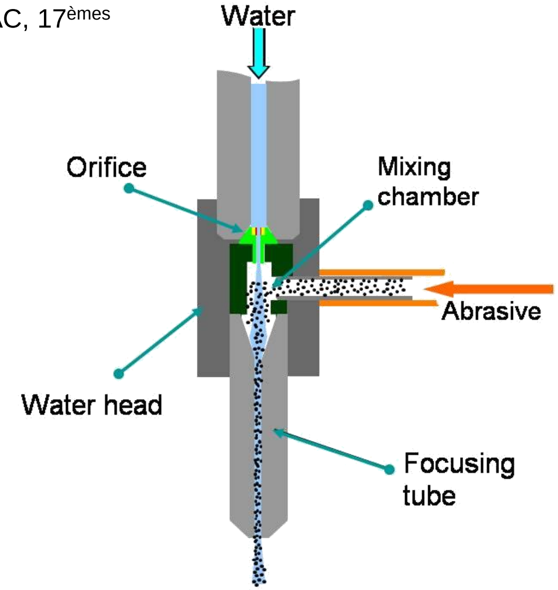
Phase 5: after double bucking

Prediction of bonding failure the between phase 4 and 5

16) Manufacturing and machining of the evaluators: Abrasive Water Jet

Cénac, F., Collombet, F., Zitoune, R., Déléris, M., « Usinage des Composites par Jet d'Eau Abrasif », AMAC, 17èmes Journées Nationales sur les Composites (JNC17), Jun 2011, Poitiers-Futuroscope, France. pp.163.

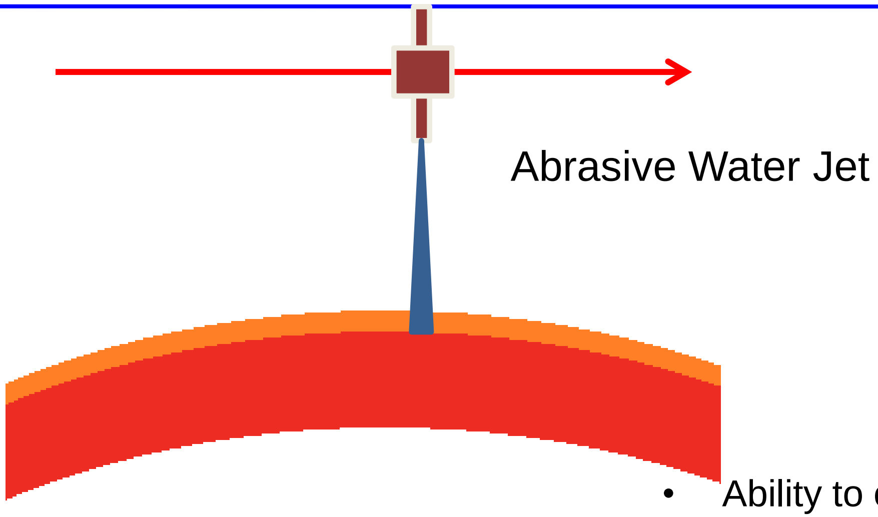
Abrasive Water Jet Machine of ICA lab (France)

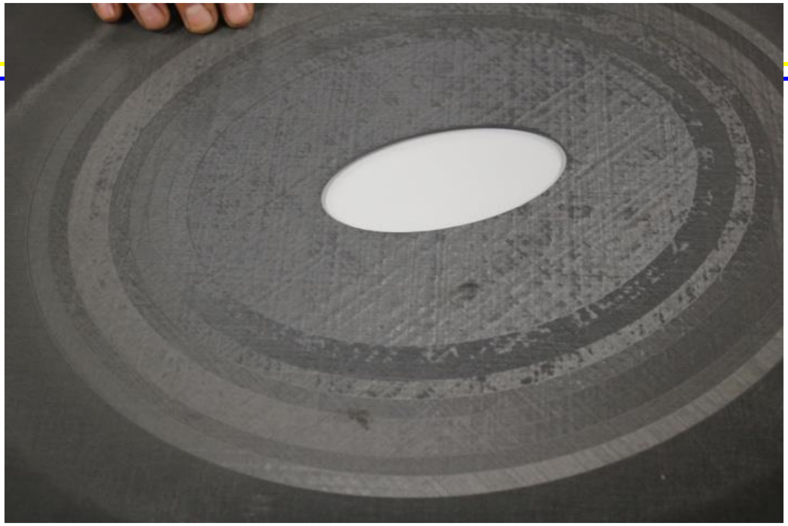


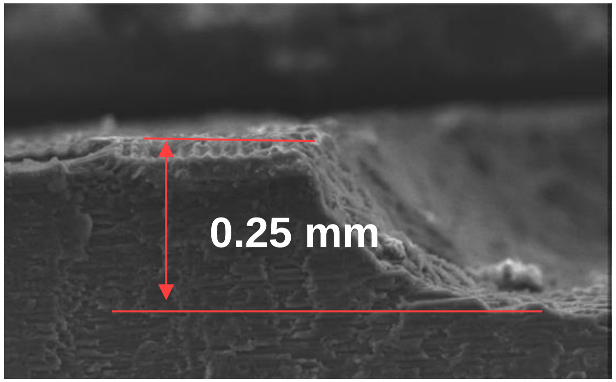
Operating principle of the cutting head

Machining parameters	Cutting	Machining carbon/epoxy
Pressure of the water	~3800 bar	From 600 to 1000 bar
Feed speed	600 $m.min^{-1}$ for 5 mm aluminum	from 6000 to 15000 $m.min^{-1}$
Abrasive flow	~400 $g.min^{-1}$	~100 $g.min^{-1}$
Head height	2.5 mm	~100 mm

16) Manufacturing and machining of the evaluators



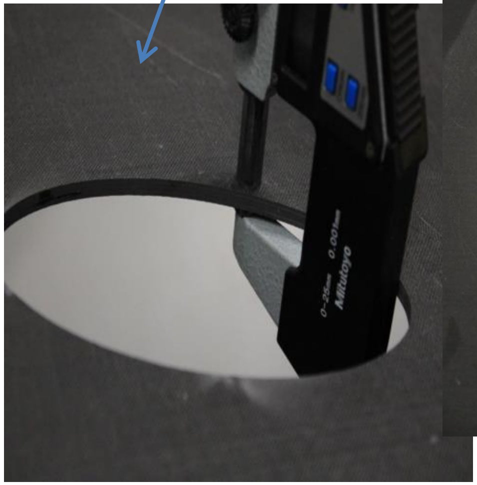


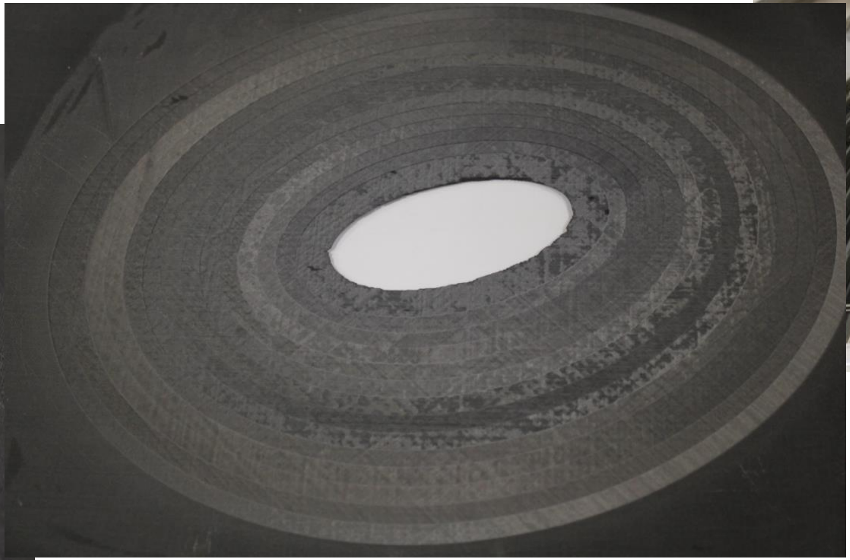


- Ability to create a machining with a **constant width** on a 3D part without a knowledge of the part or without probing
- Ability to « peel » the composite part, ply by ply, in order to **maximize the adhesion** of the patch on the mother surface
- **No delamination** initiated by the water jet during the machining phase
- No recovery of the **moisture** if the machining phase is made during a reasonable time
- Low machining loads **(only a few Newton)**
- Less volatile dusts than a machining with cutting tools

16) Manufacturing and machining of the evaluators

- Use of aluminum masks for each ellipse (15)
- The machining is hard on the last ply, altering it (need of a martyr ply?)
- Measurement of the final thickness after each machining of one ellipse





16) Manufacturing and machining of the evaluators

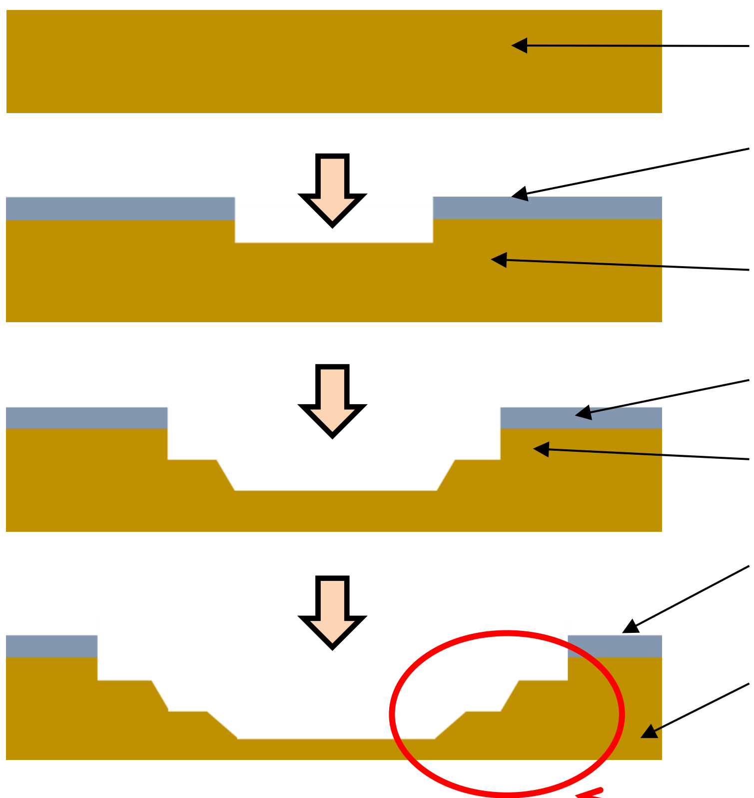
Mask number	Final measured plate thickness (mm)	Thickness machined (mm): target 0.28 mm	Difference with the mean ply thickness (mm)	Notes	Machining time
15	4.08	0.33	0.05	4960 mm/min	37min18s
14	-	-	-	Increase of the speed → 6800 mm/min	30min
13	3.56	0.26	-0.02		29min
12	3.27	0.29	0.01	Reduction of the speed → 6548 mm/min	26min30s
11	2.98	0.29	0.01	Increase of the speed → 6674 mm/min	25min
10	2.68	0.3	0.02		20min30s
9	2.42	0.26	-0.02	Increase of the speed → 7415 mm/min	17min30s
8	2.18	0.24	-0.04		17min
7	1.91	0.27	-0.01		12min30s
6	1.75	0.16	-0.12		12min
5	1.36	0.39	0.11	Reduction of the speed → 6316 mm/min	13min
4	1.12	0.24	-0.04	Increase of the speed → 7000 mm/min	11min30s
3	0.87	0.25	-0.03		8min30s
2	0.54	0.33	0.05		7min
1	-	-	-	Increase of the speed → 10000 mm/min Last ply to be cut before repair (teared)	5min

Total machining time: **4h30** (without the time of the plate thickness measurement after each machining)

EXAMPLE: Airbus → 14 plies = 28h for a manual machining

16) Manufacturing and machining of the evaluators

Milling from the inside to the outside of the repair zone.



Progressive **decrease of the acuteness** of the edge between steps along the different phases (first step)

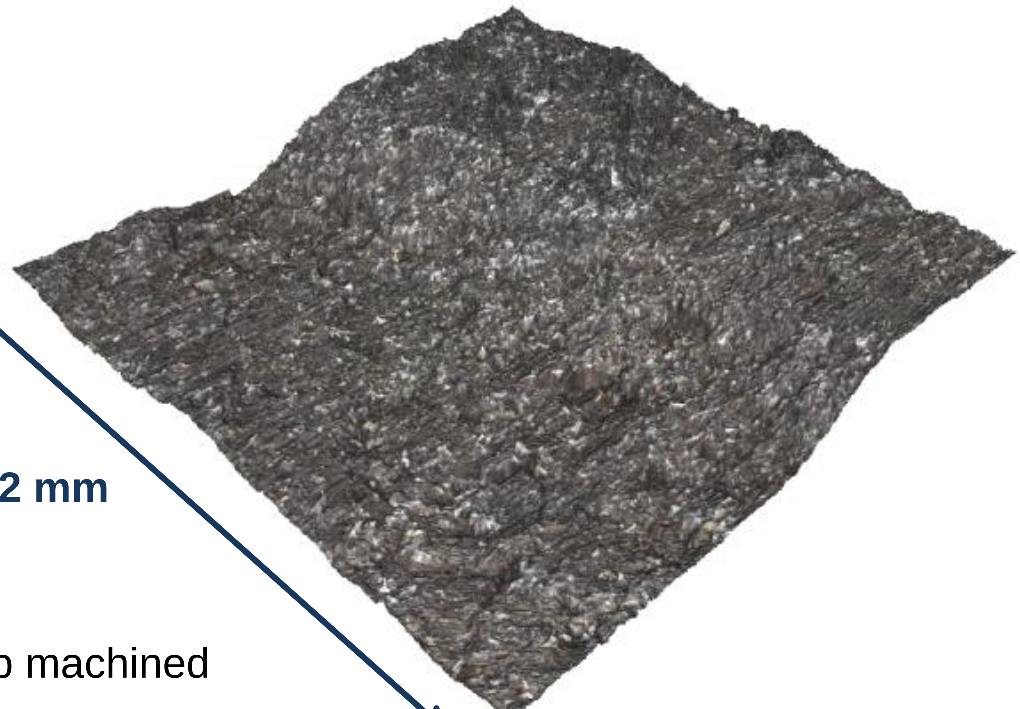
16) Manufacturing and machining of the evaluators

- Use of Alicona optical 3D surface measurement system
- Profiles of the 1st machined step and the last machined step

→ Erosion and smoothed surface

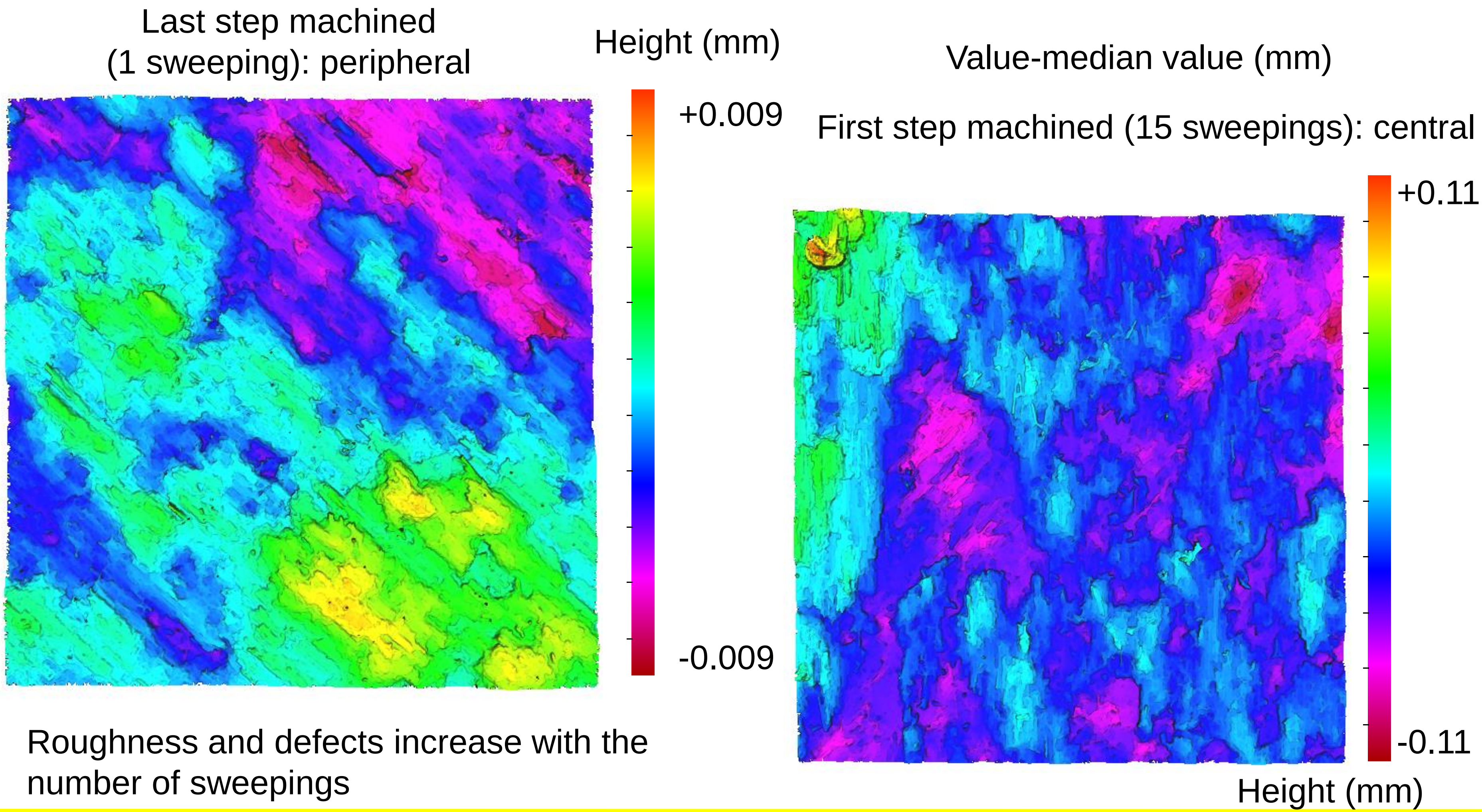
Last step to be machined

2 mm



First step machined

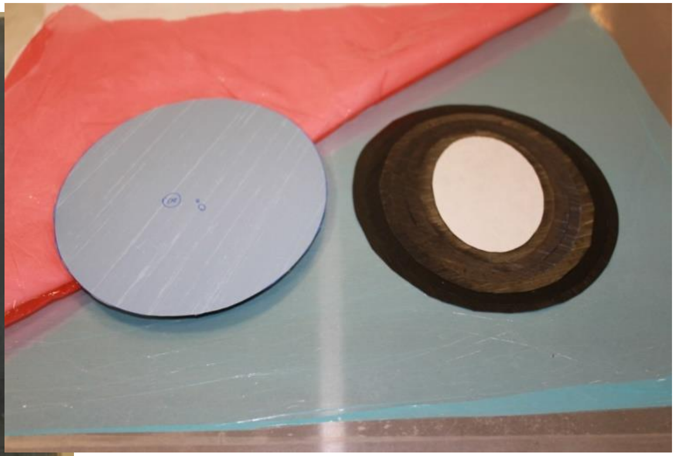
16) Manufacturing and machining of the evaluators



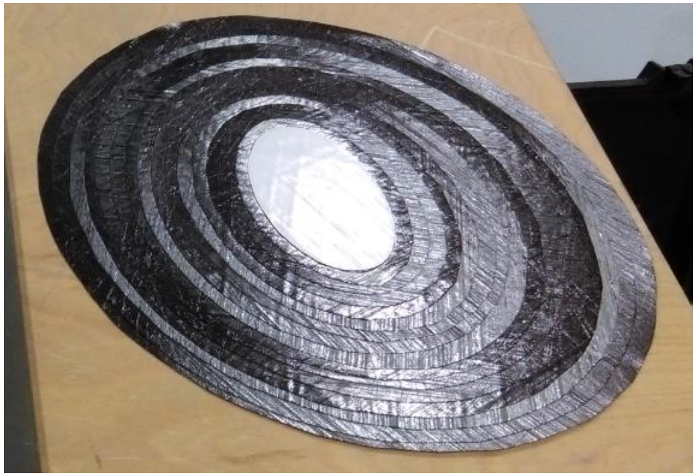
Roughness and defects increase with the number of sweepings

16) Manufacturing of the evaluators: repair patch lay-up

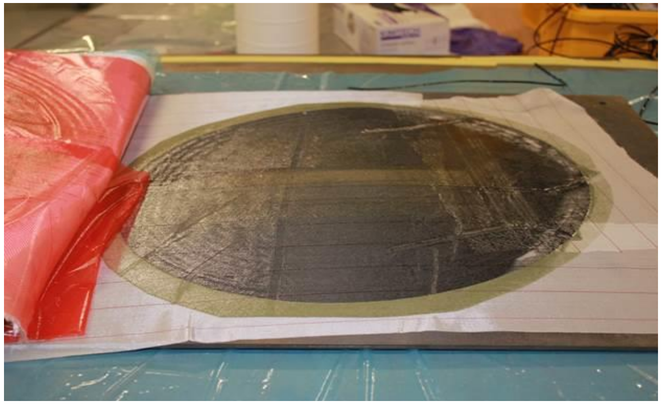
Machined evaluator



Patch lay-up



Repair patch



Stacking sequence “quasi-iso”:

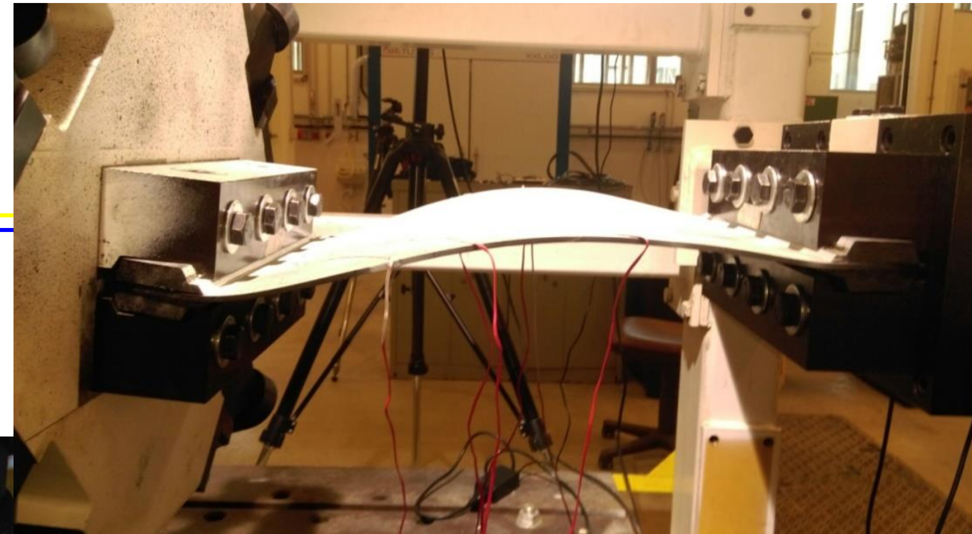
- 17 (16+1) plies HexPly® UD M10 CHS,
- [0/0/45/90/-45/-45/90/45/0/0/45/90/-45/-45/90/45/0].

One more ply for always placing two plies with the same fiber orientation on both sides of step

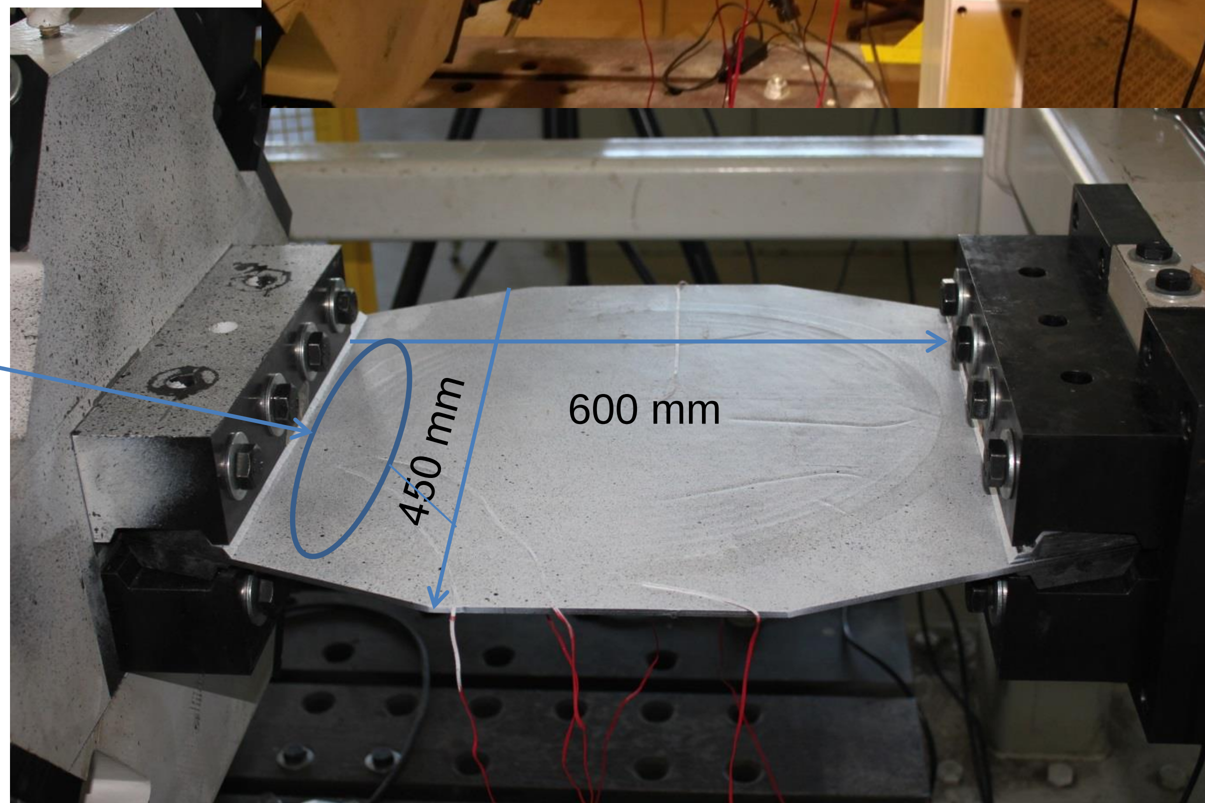
Repaired evaluator during the demolding phase

17) Evaluator test

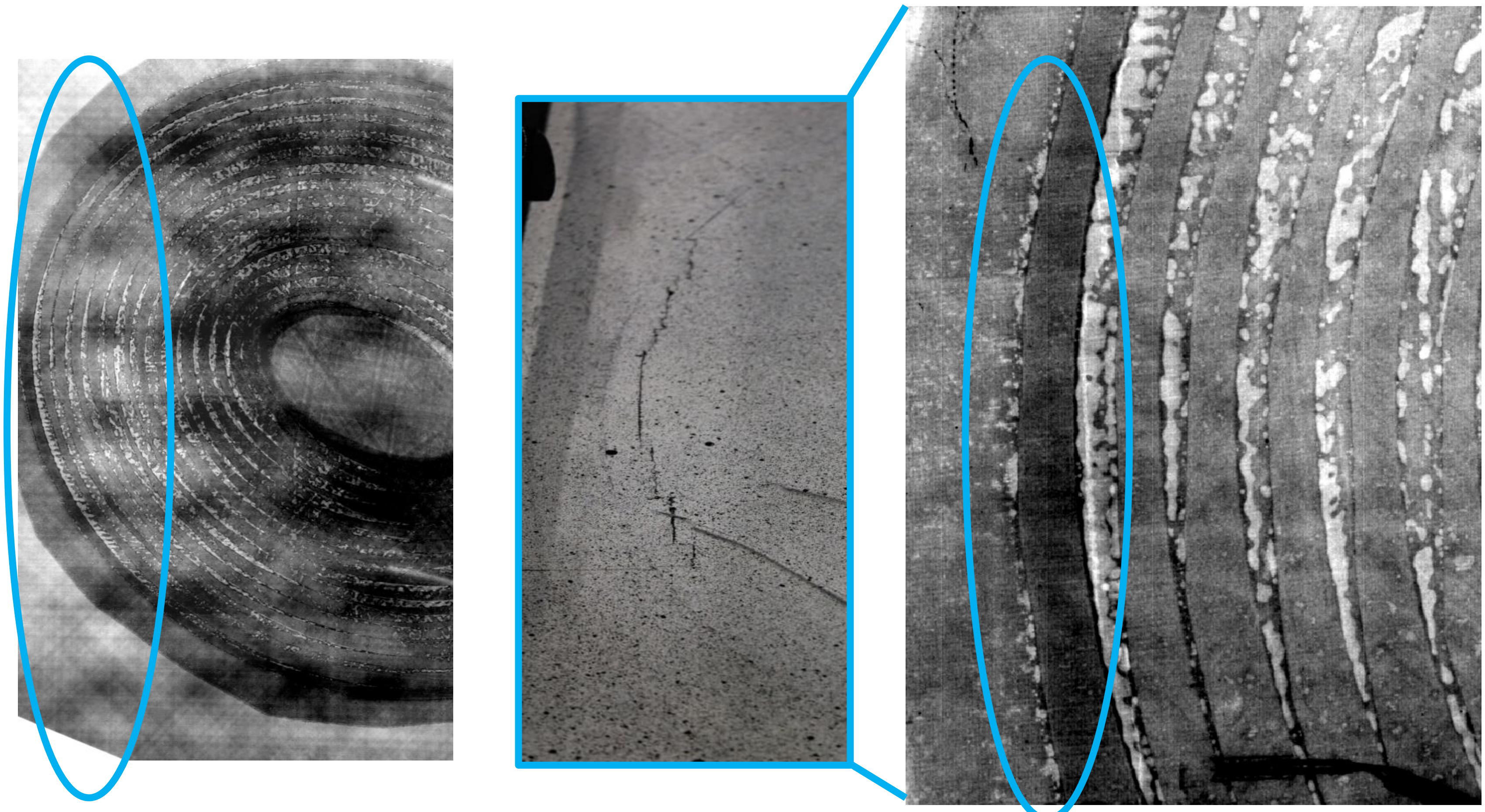
Good evaluation of the bonding joint rupture in terms of location and quality of bonding repair



Crack through the last ply: earlier (end of the step 4) than the theoretical prediction (between step 4 and 5) from a real defect



18) Post mortem tomographic analysis



Appearance of crack in the bonding zone in the chosen localization due to a bonding defect

19) Conclusion and prospects

- First phase experiments and numerical modelling have been conducted on 200 mm x 30 mm coupons: order of magnitude of local values at failure for the bonded interface
- Light modelling has been settled before implementing a whole modelling strategy:
  - 2D: shell composite elements for composite parts,
  - 3D: volume elements for the adhesive film,
  - Rigid Beam Element to link the composite parts all together and create the steps of the repair.
- In house mode failure indicator has been chosen from failure criterion found in the literature
- Design of a technological evaluator has been created from precise specification (elliptic repair, detail dimensions etc.) and complex kinematics leading to disbond the repair patch
- The evaluators have been made and machined with Abrasive Water Jet
- Multiaxial mechanical test led to rupture for the expected localization
- Generic method for repair analysis can be assessed by aeronautic industry and at the disposal of the certification evolution