Design of a test for thermo-oxidized adhesively bonded joints for aero-engines applications

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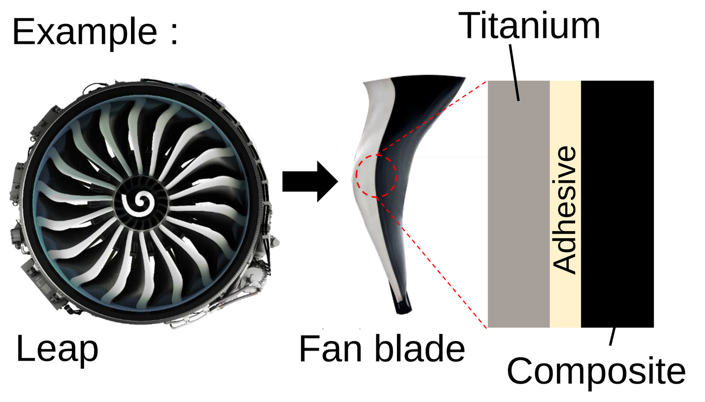
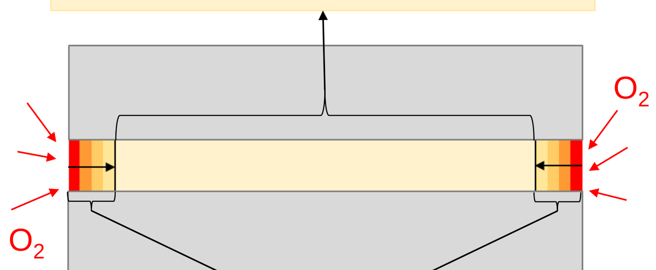
Context and objectives

Aeronautical context:

Issues: Reduce CO_2 emissions + costs → weight reduction of the structures

Solutions: - Composite materials - **Adhesively bonded assemblies**





- More sensitive to environment
- Temperature increase of futures engines

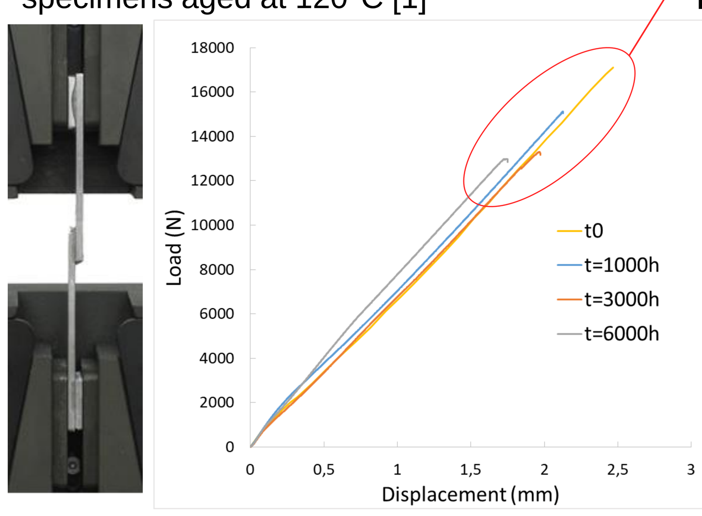
Problems

Thermo-oxidation (TO):
→ Heterogeneous degradation
→ No saturation

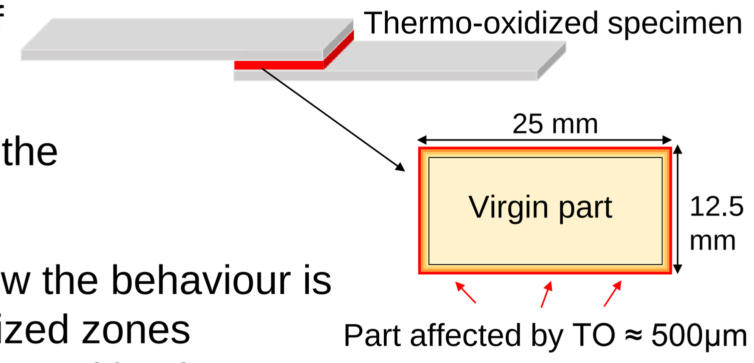
Objectives:
→ To characterise **thermo-oxidation** effects on the mechanical behaviour of **bonded assemblies**
→ Assess the impact on durability: predict the failure of the **joint**

Are tests that exist to characterise the mechanical behaviour of bonded joints suited in the context of TO?

Single lap joint (SLJ) shear test for specimens aged at 120°C [1]



One information: Decrease of the fracture load with TO



BUT
- No information on how the behaviour is impacted in the oxidized zones
- Global response governed by the behaviour of the virgin part

→Not adapted for studying TO of assemblies

Development of an adapted test by reasoning differently:
- Maximize edge effects
- Detect the initiation of a crack in the oxidized zone

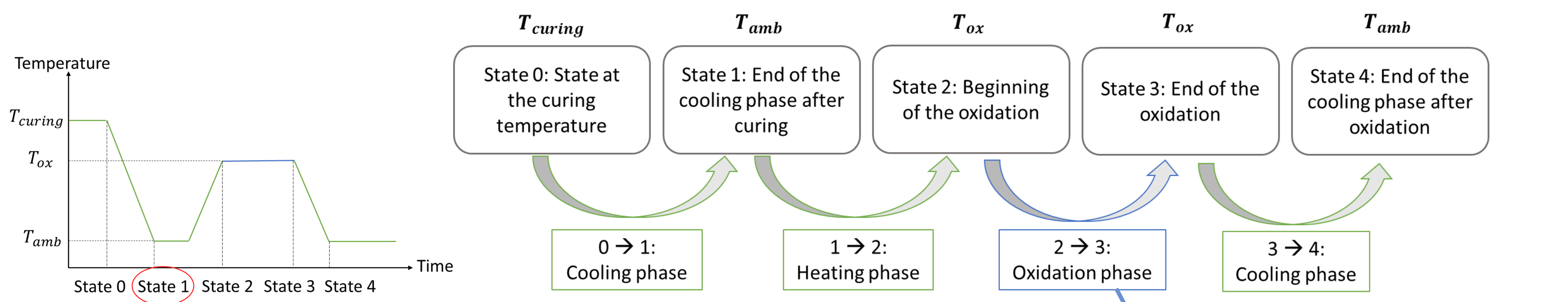
Need of a model taking into account TO

To design the test
→ Discriminate configurations more sensitive to TO

To analyse the results of the test
→ Experimental curve = virgin material + thermo-oxidized parts

I. Numerical model taking into account TO

General presentation of the model → Idea: To mimic an ageing experience

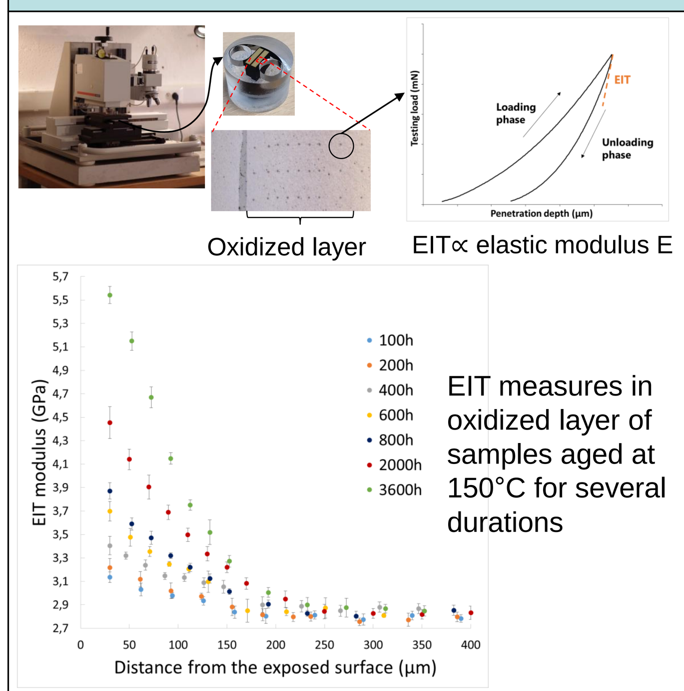


Initial state of the assembly:
consideration of residual post-curing stresses → Non negligible

How to model the gradients associated with TO?

What are the effects of TO on the adhesive? Experimental facts:

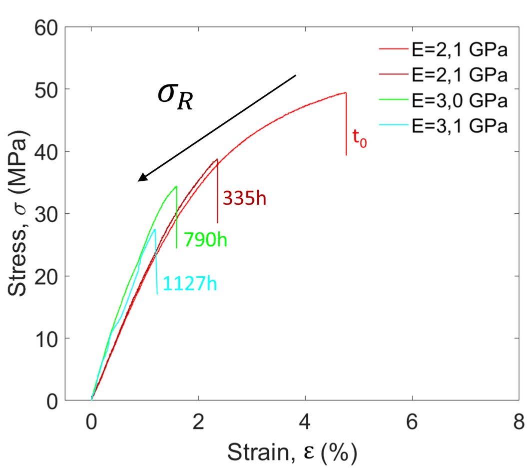
Increase of the elastic modulus



EIT measures in oxidized layer of samples aged at 150°C for several durations

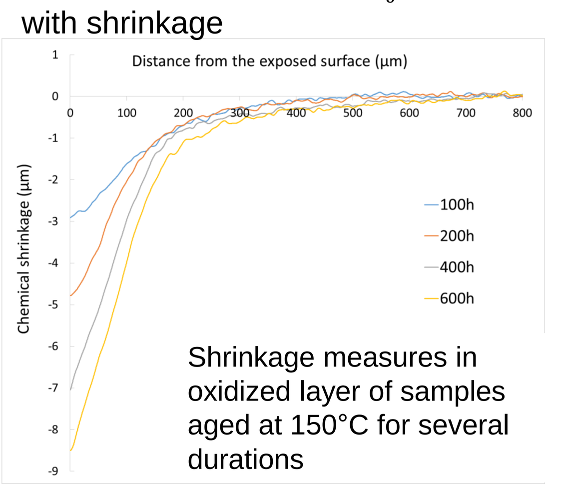
Decrease of the failure stress

Tension tests on thermoset aged at 120°C for several durations [1]



Inelastic strains of chemical origin

O_2 + macromolecular chain
↳ departure of volatiles
→Mass loss / volume variation:
Chemical strains $\varepsilon_{CH} = \frac{1}{3}\frac{\Delta V}{V_0}$ associated with shrinkage



Shrinkage measures in oxidized layer of samples aged at 150°C for several durations

How to model TO gradients? Use of a phenomenological **parameter representative of TO progress** γ [2]

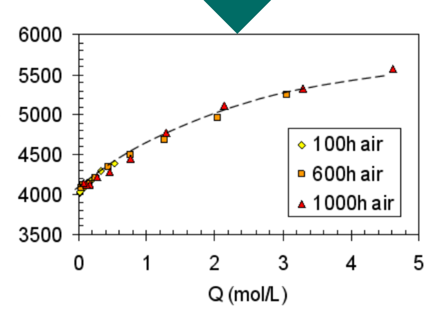
$$\gamma = \frac{EIT}{EIT_0} - 1$$

Evolution of the parameter with a diffusion-reaction like equation:

$$\frac{\partial \gamma}{\partial t_{ox}} = \kappa \frac{\partial^2 \gamma}{\partial x^2} + R(\gamma)$$

Boundary conditions:
- $\gamma(x,0) = 0$
- $\gamma(0,t_{ox}) = \gamma_{max}(t_{ox})$

Based on



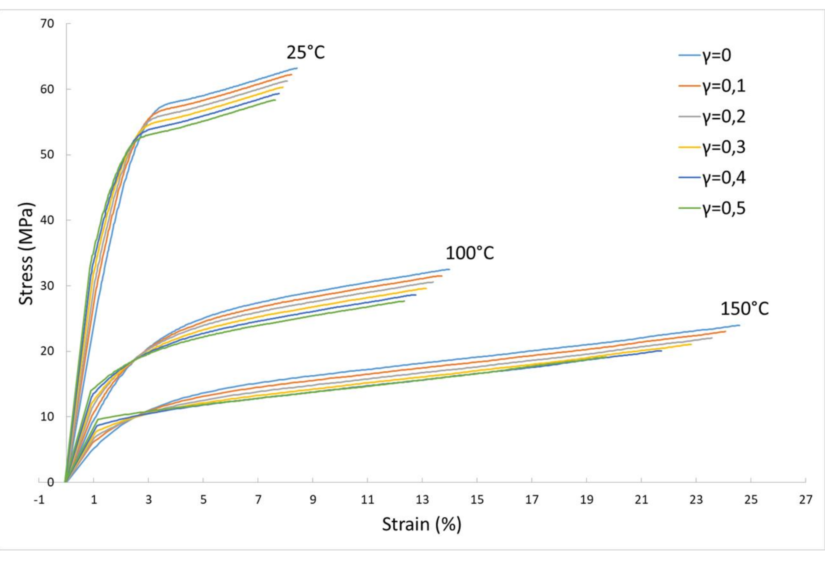
Correlation between elastic indentation modulus EIT and concentration of oxidation products Q [3]

$$Q = \int_0^t \frac{d[O_2]}{d\tau} d\tau$$

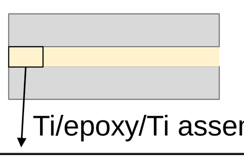
To model properties gradients: link them to γ

$$E(\gamma) = E_0(\gamma + 1)$$
$$\sigma_R(\gamma) = B.\gamma + \sigma_R^0$$
$$\varepsilon_{CH}(\gamma) = \alpha_{CH}.\gamma$$

Behaviour of the adhesive as a function of the temperature and the ageing parameter γ

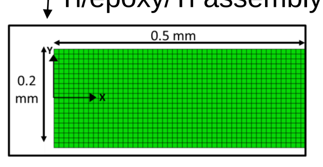


Results with this numerical method:

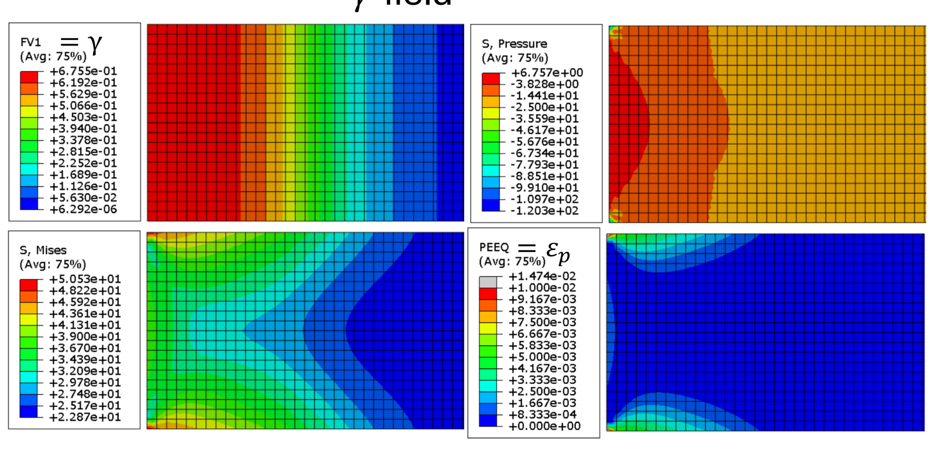


Ti/epoxy/Ti assembly

- Assessment of the stress state within the adhesive after ageing before testing the specimen



- Behaviour of the adhesive within the oxidized layer dependent of the γ field



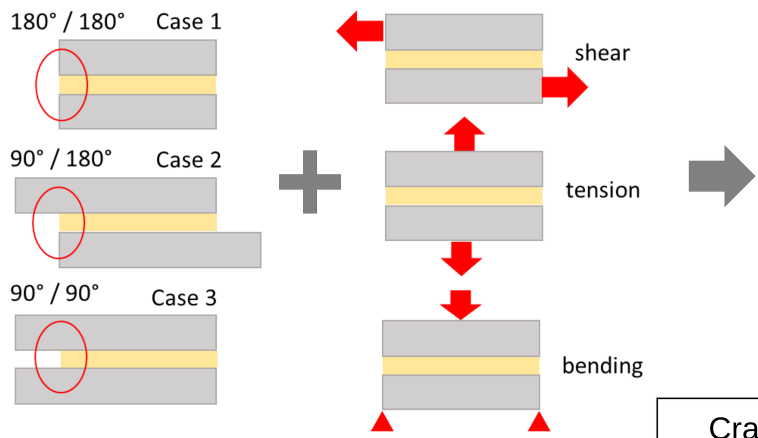
II. Strategy to design a test adapted for adhesively bonded joints aged by TO

Strategy to assess the sensitivity of a configuration to TO and define an optimal configuration:

For a given geometry of the adhesive

3 singularities possible:

3 types of simple loading:



How to discriminate these configurations regarding sensitivity to TO?

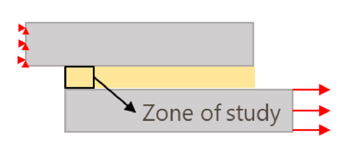
→Comparison between:

Virgin assembly: taking into account post-curing stresses VS **Oxidized assembly:** with model taking into account TO

One simple criterion:

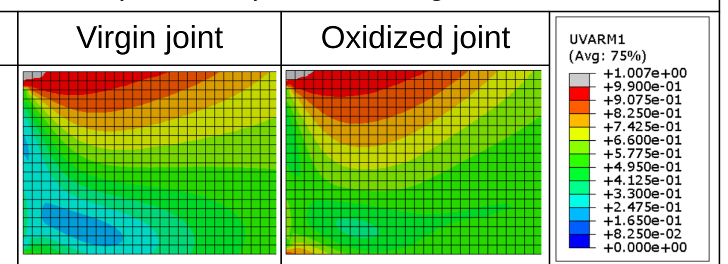
Failure stress: **initiation of crack**
→ $\sigma > \sigma_R(\gamma) \leftrightarrow \frac{\sigma}{\sigma_R(\gamma)} > 1$ / $UVARM1 = \sigma/\sigma_R(\gamma)$

Example for one configuration:



Case 2 / shear

Crack initiation indicator (UVARM1) → Reaching of failure stress

	Virgin joint	Oxidized joint
Fields of crack initiation indicator		
Crack initiation load	2360N	1785N

-24%

Final comparative table:

		Shear Case 1	Shear Case 2	Shear Case 3	Tension Case 1	Tension Case 2	Tension Case 3	Bending Case 2
Crack initiation load	Virgin	2500N	2360N	2675N	28490N	28870N	20225N	1415N
	Oxidized	2100N	1785N	1985N	19440N	20560N	11975N	1065N
	Reduction of load	**16%**	**24%**	**26%**	**32%**	**29%**	**41%**	**25%**

Discrimination of the sensitivity of the configurations to TO with the reduction of the crack initiation load

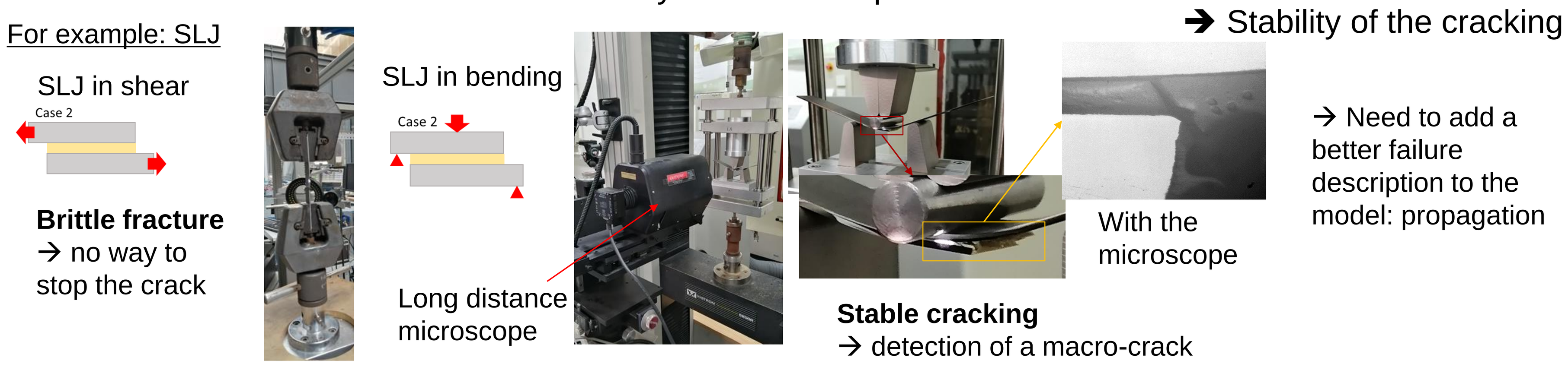
Numerical analysis on crack initiation through a simple criterion: not enough to conclude
→ Need to consider other experimental aspects

Experimental aspects:

- Feasibility: industrial context, better to adapt existent test than develop a new one
- Detection of crack initiation in the oxidized layer: need to capture macro-crack before failure

→ Stability of the cracking

For example: SLJ



Brittle fracture
→ no way to stop the crack

Stable cracking
→ detection of a macro-crack

→ Need to add a better failure description to the model: propagation

IV. Conclusion et perspectives

CONCLUSION

- Aeronautical context: increasing use of adhesively bonded joints → TO
- Aim: To characterise the effects of TO on the behaviour of bonded assemblies
  → Current tests not adapted: TO = surface/edge phenomenon+ no saturation
  → Need to design an adapted test associated with a model taking into account TO
- Model used for the design of the test: simple criterion to assess the sensitivity to TO
  → Not enough to choose optimal configuration: need to consider other experimental aspects

PERSPECTIVES

→Add the influence of geometric parameters (length, thickness, width) to the sensitivity study
→Include a description of failure behaviour → stability of cracking

References

[1] J. Delozanne, PhD thesis: ENSAM, Paris (2018).

[2] M. Gigliotti, M. Minervino, M.-C. Lafarie-Frenot, J.-C. Grandidier. Mechanics of Materials N°101 (2016) 118–135.

[3] L. Olivier, N.-Q. Ho, J.-C. Grandidier, M.-C. Lafarie-Frenot. Polymer Degradation and Stability N°93 (2008) 489–497.

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