



Visco-hyperelastic modeling of aeronautical sealant in pure bonded and hybrid bolted/bonded joints

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Content

1. Introduction
2. Methodology
3. Visco-hyperelastic parameters determination
4. Assessment of joint behavior
5. Conclusion & Perspectives

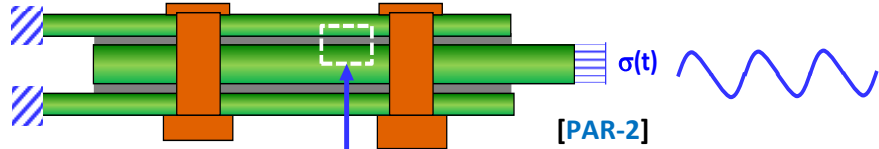
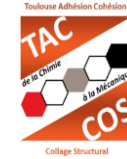


Éric PAROISSIEN



Frédéric LACHAUD

STRUCTURAL BEHAVIOR
Experimental & numerical characterization and modeling



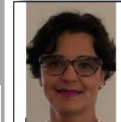
Maëlen AUFRAY

INTERFACE BEHAVIOR
Experimental characterization and modeling
Functionalization of the adhesion

MATERIAL BEHAVIOR
Experimental characterization and modeling
Functionalization of the cohesion & formulation



Valérie NASSIET



Bouchra HASSOUNE



Hélène WELEMANE

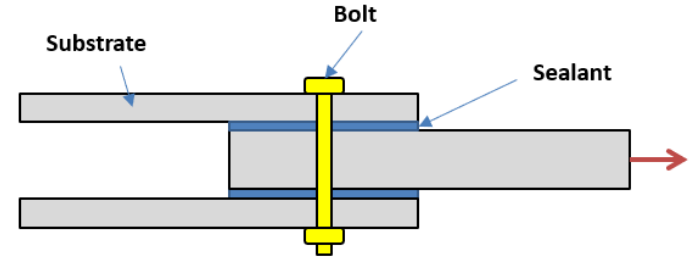
- Hybrid bolted/bonded joints offer many advantages over pure bolted or bonded joints.
- In aerospace industry, **bolted-sealed joints** with very **small stiffness sealant** are widely used.

✓ With recent developments, sealant can play a part in the mechanical function, contributing in relieving stress thanks to its viscoelastic nature

⇒ *How can the load transferred by the sealant in a bolted-sealed joint be determined?*

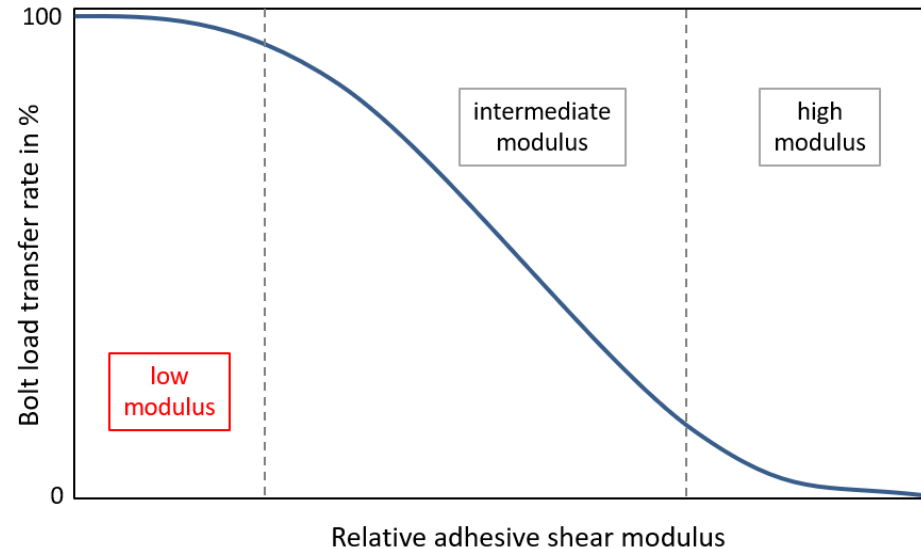
✓ Linear elasticity has difficulty representing rubber-like sealant **large time-dependent deformations**.

⇒ *How can the complex visco-hyperelastic sealant behavior be accounted ?*

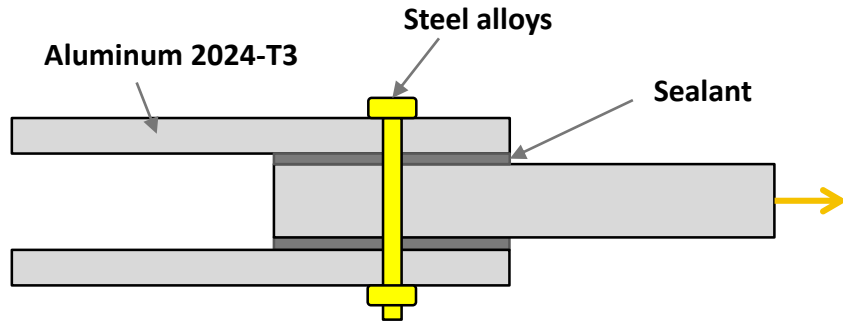
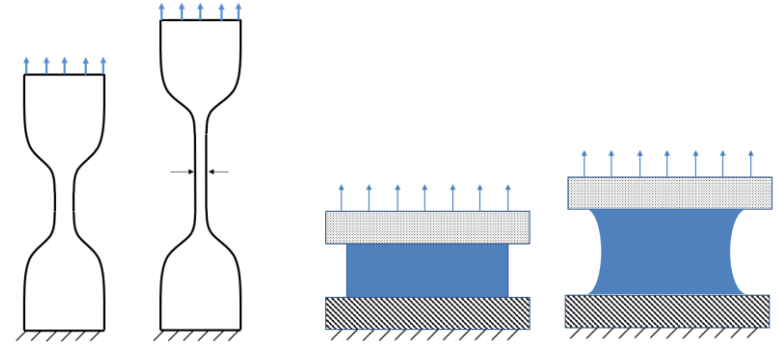


Hybrid bolted/bonded joint

[PAR-2]



- Propose a methodology to evaluate load transferred by the sealant based on numerical and experimental tests
- Present the process of determining visco-hyperelastic parameters of sealant and their applications on pure bonded and bolted-sealed joints



II. Methodology

1

Tests on sealant

- ❑ Tests on sealant: quasi-static & relaxation tests on uniaxial tensile and pure shear specimens
- ❑ **Parameter identification**

optimization

2

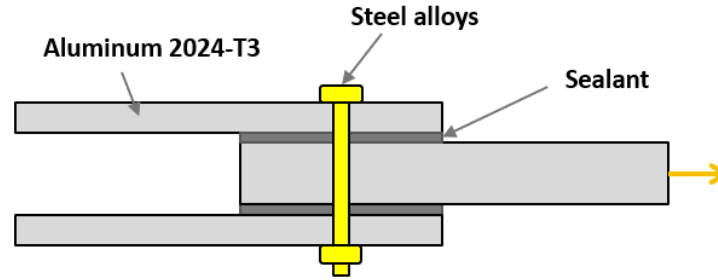
Bonded joint tests

- ❑ Experimental & **Numerical tests**
- ❑ Two configurations: 0,2 & 0,5 mm of sealant thickness

3

Bolted-sealed joint tests

- ❑ Experimental & **Numerical tests**
- ❑ Two configurations: 0,2 & 0,5 mm
- ❑ Load transfer rate calculation



- Sealant: **PR 1782 C 2**

is a two-part product based on a liquid polysulfide polymer polymerized with manganese dioxide. The putty takes 12 hours for curing under ambient conditions. [\[LJF-1\]](#)

According to thermomechanical analysis (TMA), the shear modulus of sealant in the rubbery/elastomeric state is constant over the experimental temperature range: [18 ; 24°C].

- Substrates: **Aluminum 2024-T3**

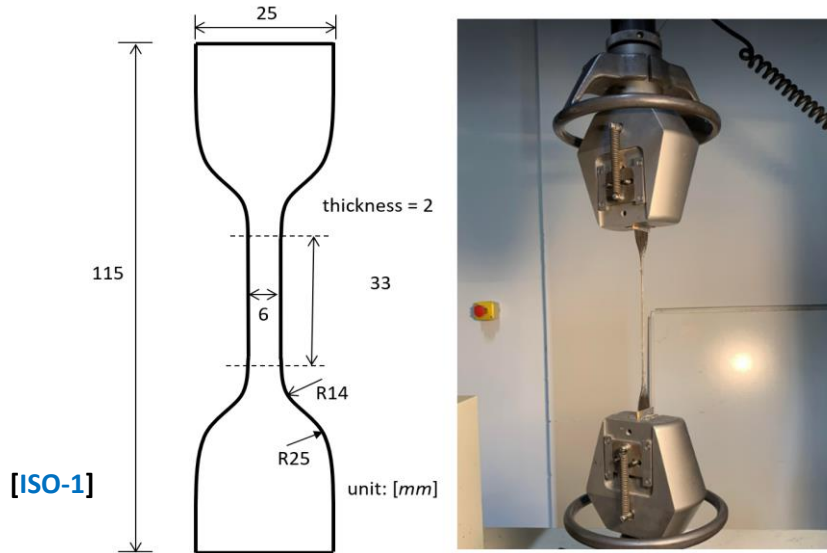
- Bolt **EN3115-3-5** [\[AEC-1\]](#) & Nut **ASNA2531-3** (Steel alloys)



EN3115-3-5

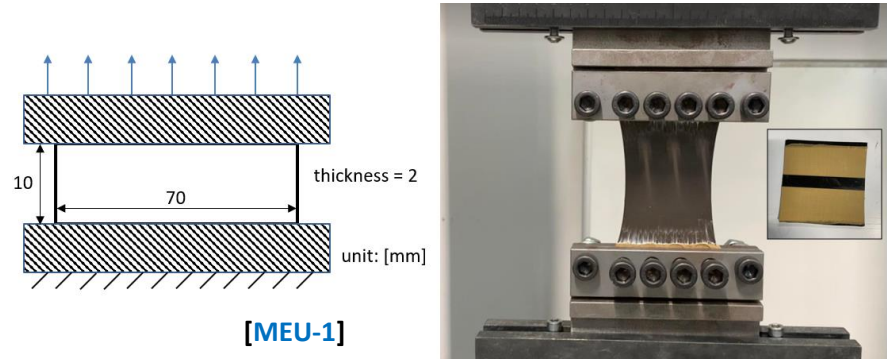
ASNA2531-3

Uniaxial tensile (UAT) test



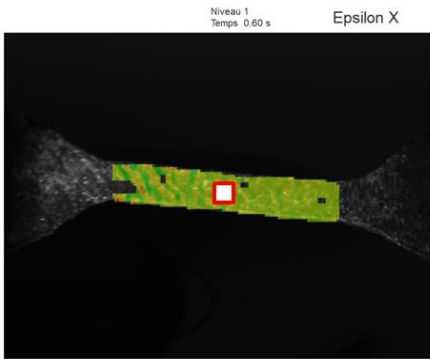
Dumbbell specimen and UAT test setting-up

Pure shear (PS) test

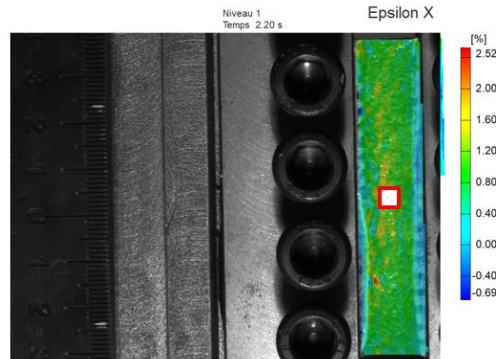


Rectangular specimen and PS test setting-up

Test speed selection



Uniaxial Tensile Test



Pure Shear Test

- Elastomeric behavior is very sensitive to test speed: same local strain rate for both tests

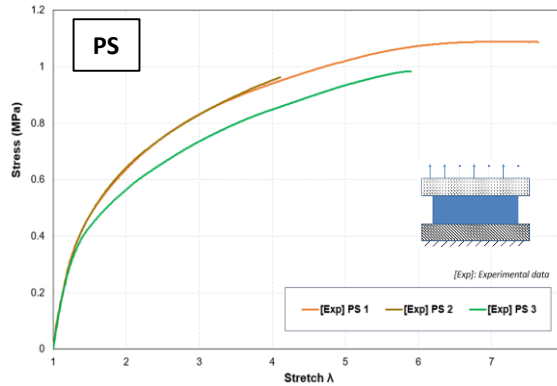
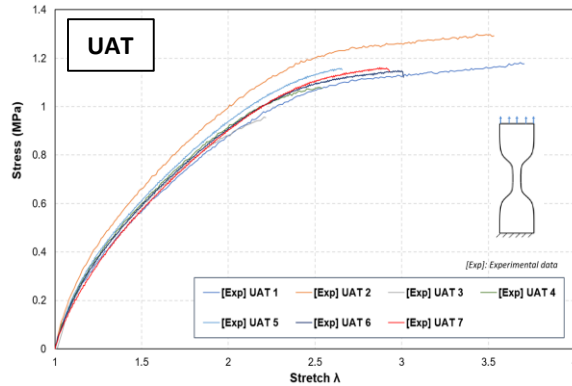
- Monitoring by Digital Image Correlation (DIC)

For a local strain rate of 0.065 s^{-1}

- UAT at **250 mm/min**

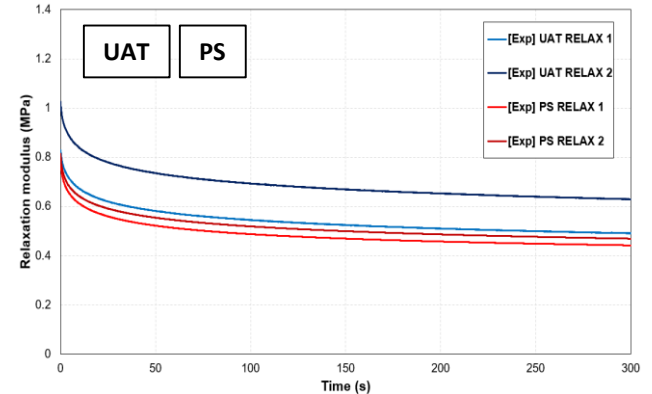
- PS at **80 mm/min**

Quasi-static tensile tests



Experimental data for UAT and PS quasi-static tensile tests

Relaxation tests

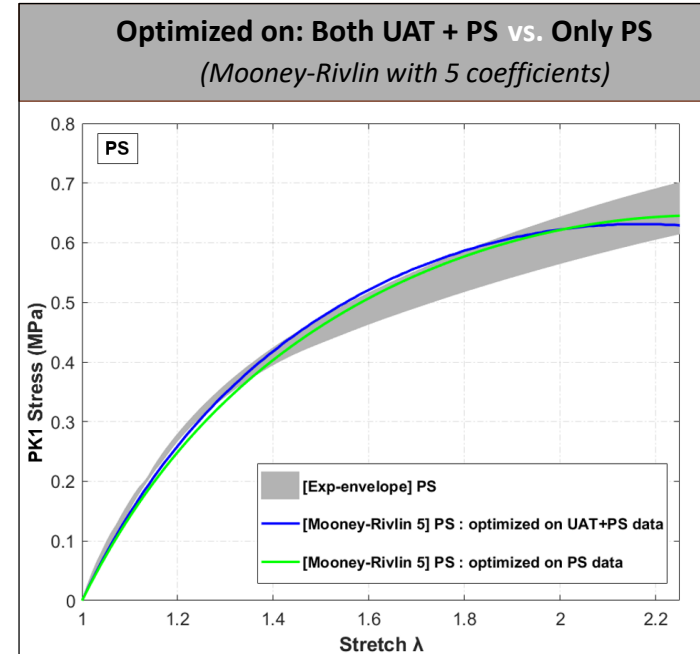
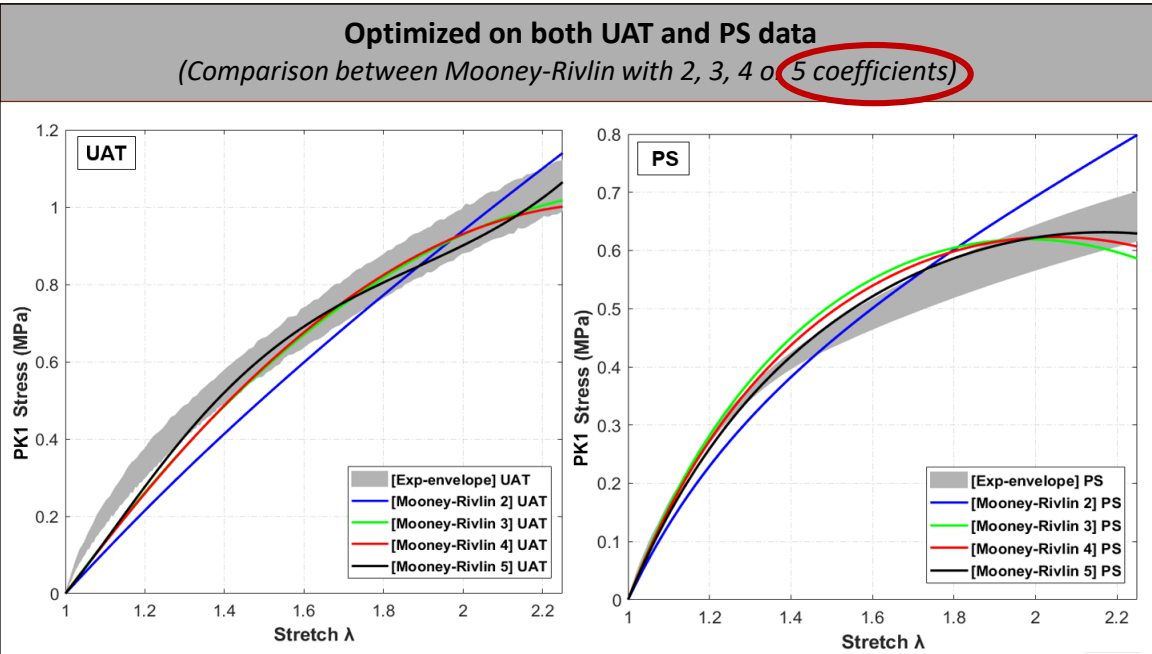


Experimental data for UAT and PS relaxation tests at strain $\epsilon = 1$

Relaxation test: in the first phase, displacement increases with time until the elongation ratio reaches 2, then deformation is kept constant and the machine continues to capture the reaction force of the specimen.

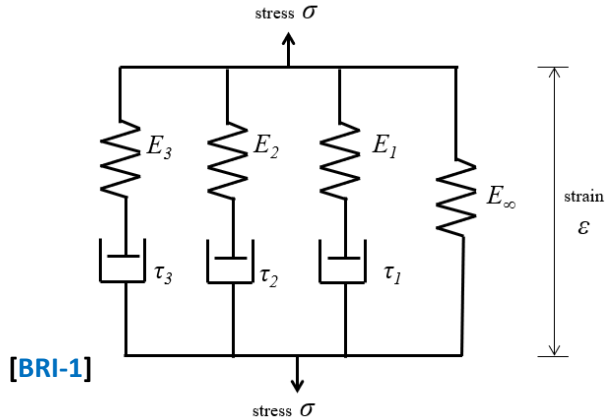
III. Visco-hyperelastic parameters determination

Idea: For each hyperelastic model, the engineering stress equations are determined as a function of the hyperelastic coefficients and elongation λ by taking the differential of the strain energy density \mathbf{W} while using the assumptions specific to each test.



✓ **The Mooney-Rivlin model with 5 coefficients is selected for this research.**

Generalized Maxwell model with 3 Maxwell arms

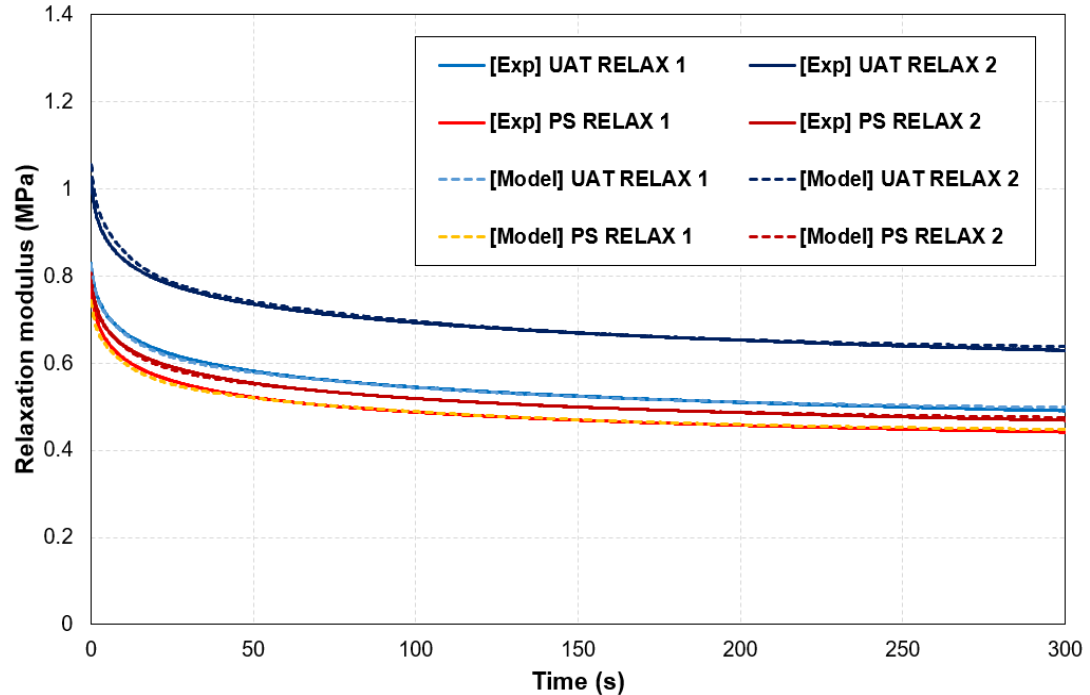


[BRI-1]

$$E(t) = \frac{\sigma(t)}{\varepsilon(t)} = E_{\infty} + \sum_{i=1}^n E_i * e^{\frac{-t}{\tau_i}}$$

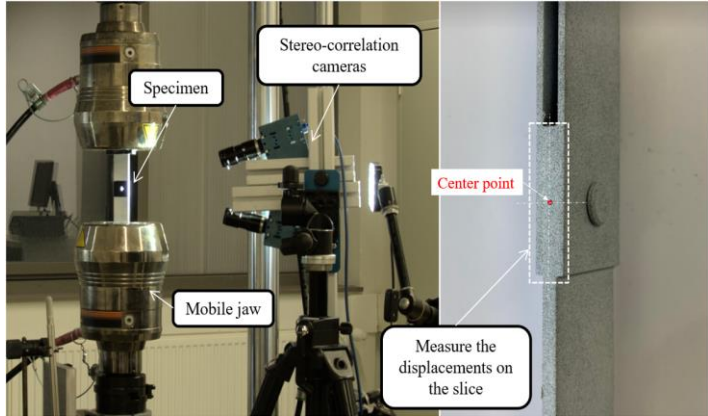
Prony series:

Maxwell arm	E_i [MPa]	τ_i [s]	g_i
$i = 1$	0.0620	1	0.0725
$i = 2$	0.1382	10	0.1615
$i = 3$	0.1472	100	0.1722



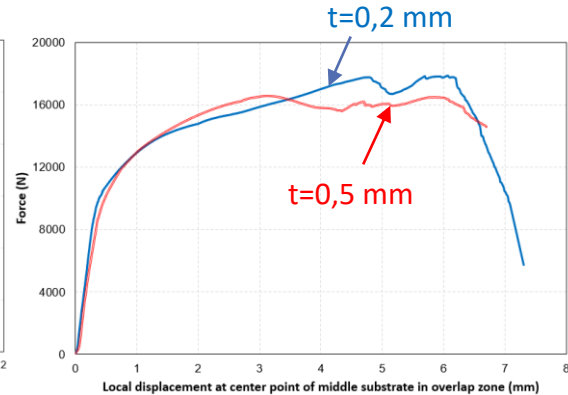
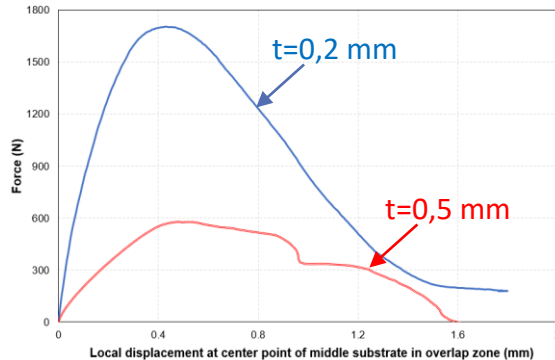
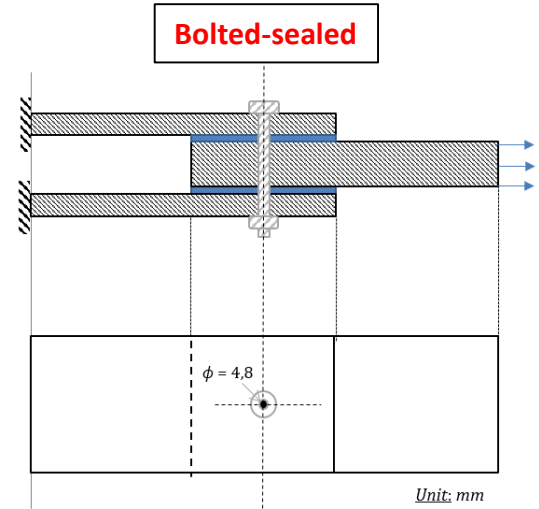
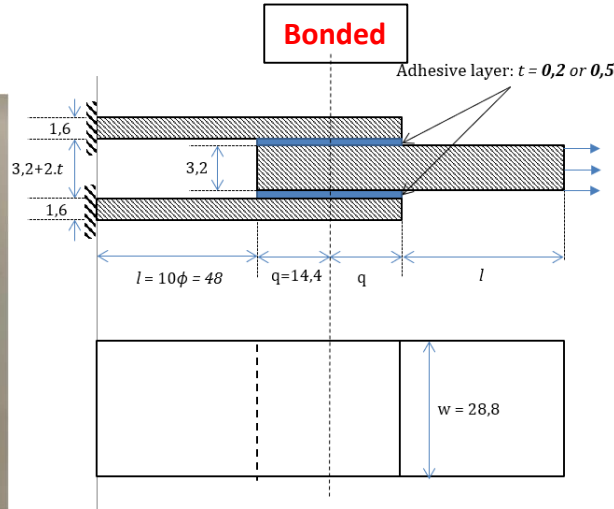
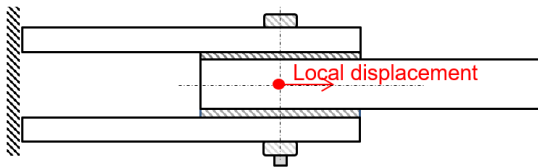
IV. Assessment of joint behavior

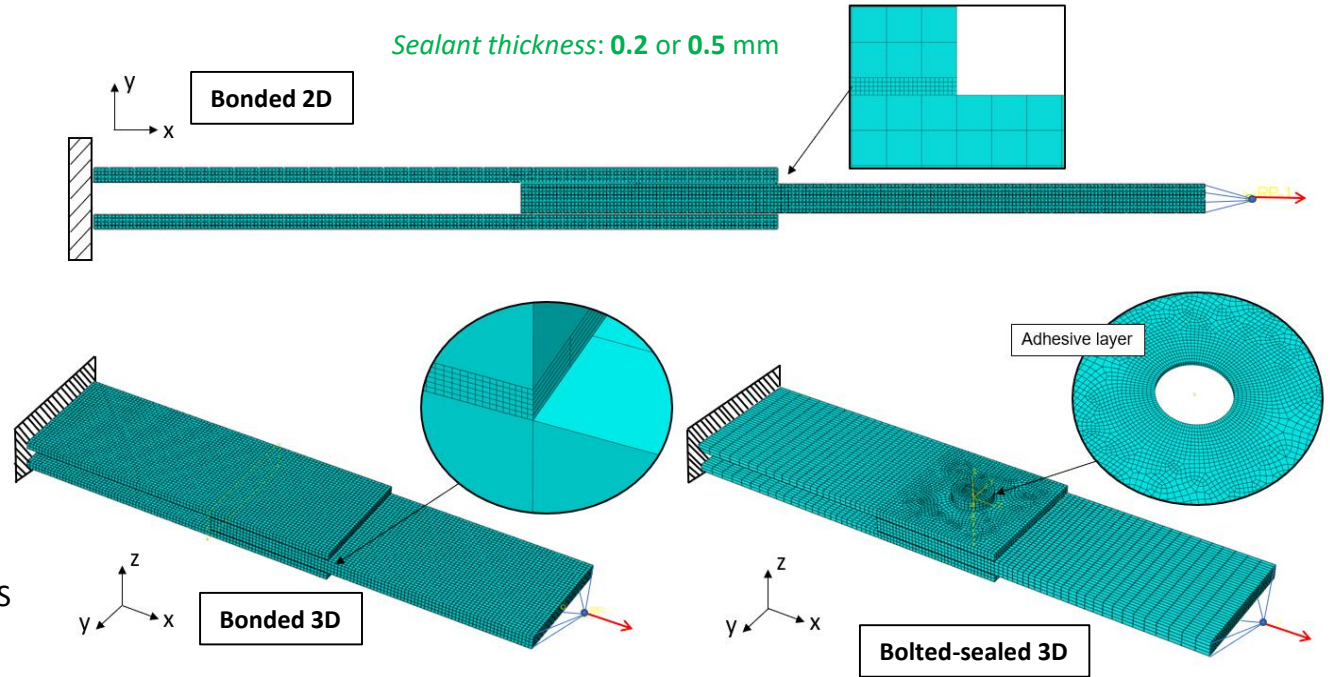
Joint tests



The test speed is **0.5 mm/min** for both the pure bonded joint and the bolted-sealed joint tests.

The relationship between applied force and local displacement at the center point of the middle substrate in the overlap zone is evaluated.





■ Tool: Simulation software ABAQUS

■ Pure bonded joint:

2D plane strain and 3D models for the comparison

⇒ Simulation tests are carried out using the 2D plane strain model to save calculation time.

■ Bolted-sealed joint: 3D model

Materials:

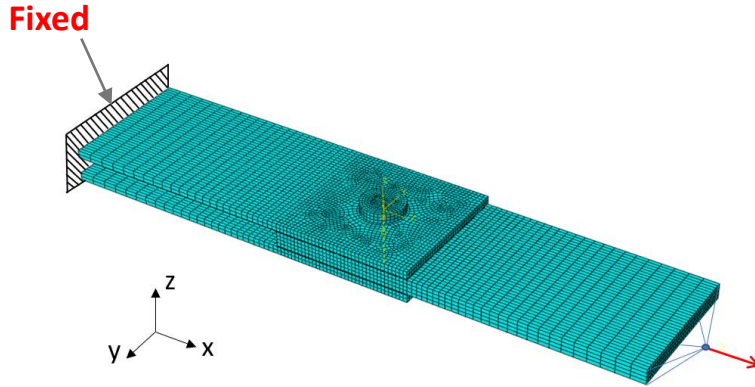
Substrates & bolt:

Material	Material properties
Al 2024-T3	$E = 72 \text{ GPa}$, $\nu = 0.33$
Steel alloys	$E = 21 \text{ GPa}$, $\nu = 0.33$
Contact "bolt-hole"	$\mu = 0.3$

Sealant:

VHE	Visco-hyperelastic: 5-coeff Mooney-Rivlin + Prony series
HE	Pure hyperelastic : 5-coeff Mooney-Rivlin

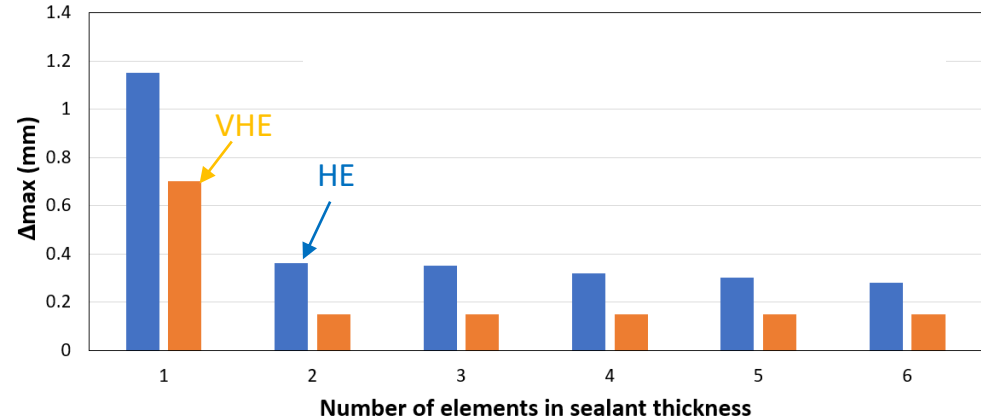
Boundary conditions:

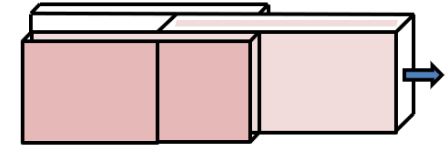
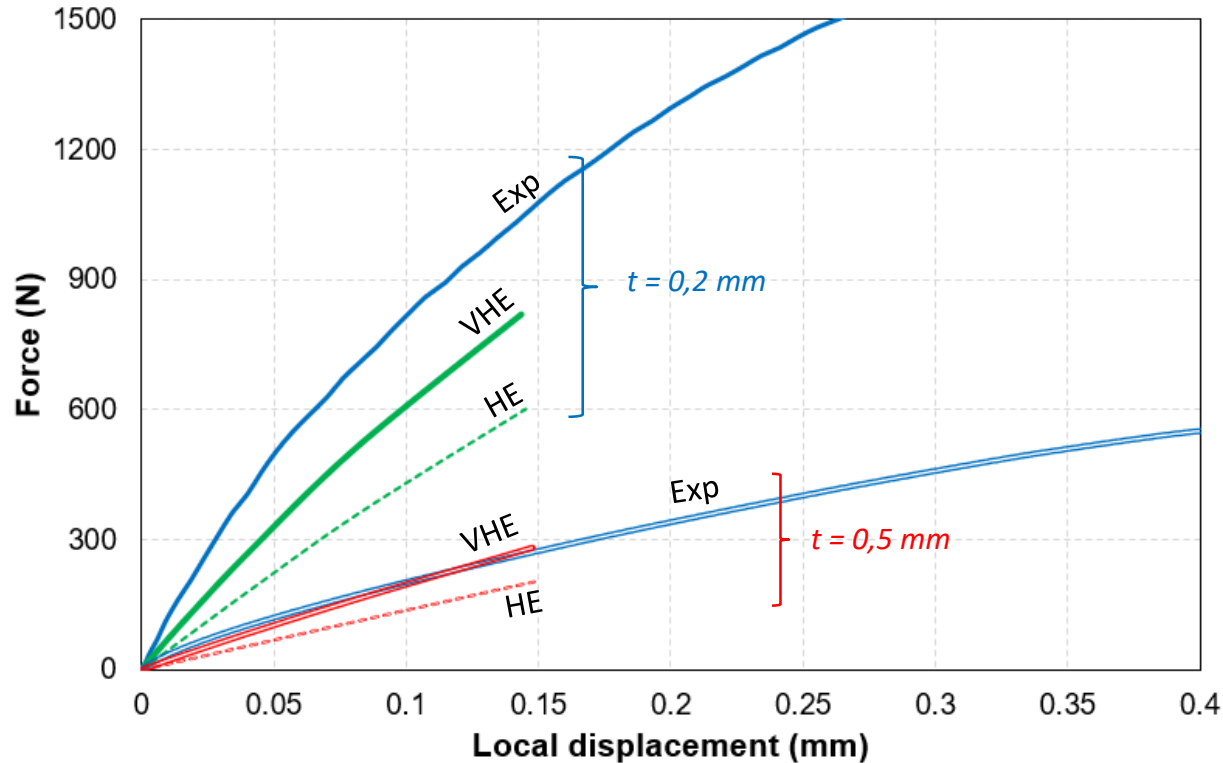


Applied displacement: 0,15 mm

- Evaluate joint behavior under low loads corresponding to fatigue state.
- Chosen according to the mesh resolution, sealant material law and convergence capability.

Maximum applied displacement for converged calculation (Δ_{max}) in mm

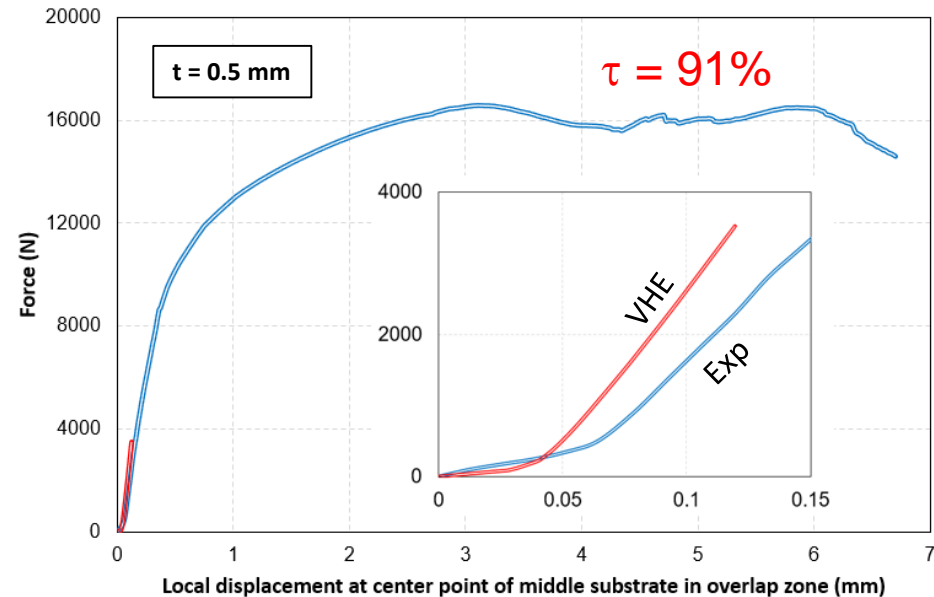
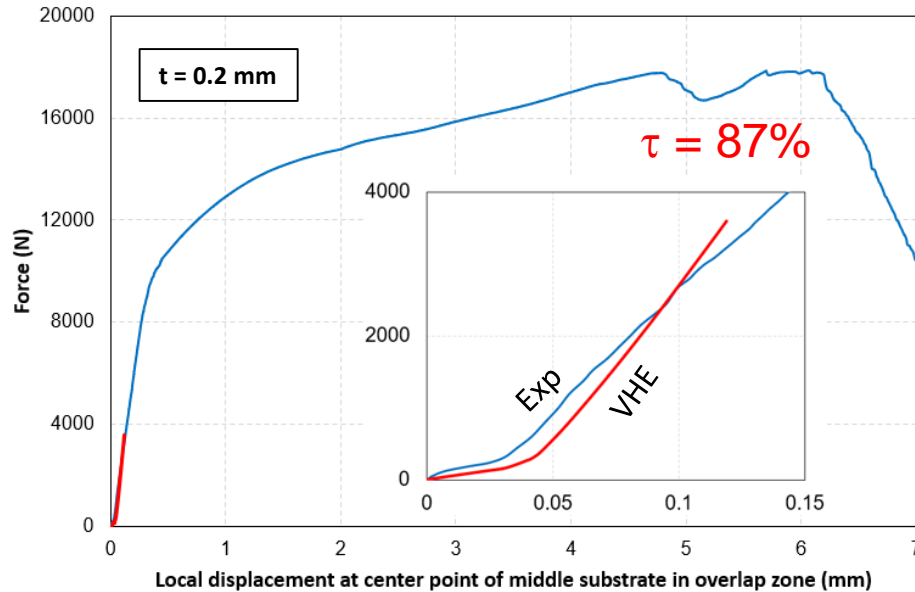
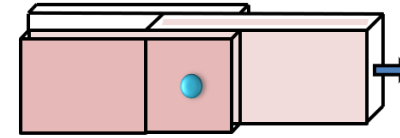




- ✓ Greater influence of the sealant for small thickness of sealant layer
- ✓ VHE represents better the joint behavior than HE

IV. Assessment of joint behavior

- **Bolt load transfer rate (τ):** is defined by the ratio of the load supported by the bolt to the total load applied.



⇒ Sealant material identification allows for bolted-sealed joint behavior modeling and the determination of load transferred by the sealant.

V. Conclusion & Perspectives

- ❑ Visco-hyperelastic coefficients **can be determined from several test data (UAT and PS)** using the presented optimization method.
- ❑ **Only PS experimental data would be needed** to predict the force transfer distributions in double-lap joints.
- ❑ The **more complex the sealant material model**, the **lower the convergence capability** of the numerical simulation.

- ❑ Increasing the load transferred by sealant could help to **improve the fatigue life** of the bolted-sealed joint
- ❑ An idea for increasing the fatigue strength of an bolted-sealed joint by **reinforcing the sealant formulation** will be developed.

14TH EURADH & 7TH WCARP 2023

THANK YOU
Any questions?

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REFERENCES

- [**AEC-1**] AECMA, prEN6115-P5 (Aerospace Series, Bolts), European Association of Aerospace Industries (2007)
- [**ATR-1**] A. Atre, W. S. Johnson, Analysis of the effects of interference and sealant on riveted lap joints, *Journal of Aircraft* (2007), vol. 44, No. 2
- [**AUS-1**] P.E. Austrell, Modeling of Elasticity and Damping for Filled Elastomers, Report TVSM 1009 (1997).
- [**BON-1**] L. Boni et A. Lanciotti, Fatigue behavior of double lap riveted joints assembled with and without interfay sealant, *Fatigue & Fracture of Engineering Materials and Structures* 34 (2010) 60-71
- [**BRI-1**] L.C. Brinson, T.S. Gates, *Comprehensive Composite Materials*, 2000
- [**CAB-1**] M. Cabello et al, A non-linear hyperelastic foundation beam theory model for double cantilever beam tests with thick flexible adhesive, *International Journal of Solids and Structures* (2015),
- [**DEC-1**] C. Dechwayukul et al, Analysis of the effects of thin sealant layers in aircraft structural joints, *AIAA journal* (2003), vol. 41, No. 11
- [**HOA-1**] C.T. Hoang-Ngoc, E. Paroissien, Simulation of single-lap bonded and hybrid (bolted/bonded) joints with flexible adhesive, *International Journal of Adhesion & Adhesives* 30 (2010) 117–129
- [**ISO-1**] ISO 37:2005(E): Rubber, vulcanized or thermoplastic: Determination of tensile stress-strain properties
- [**KAM-1**] N. Kammerdtong, The shear properties of a polymer sealant and analyses of the distortion and fatigue of sealed countersunk riveted lap joints, PhD thesis (2001)
- [**KEL-1**] G. Kelly. Quasi-static strength and fatigue life of hybrid (bonded/bolted) composite single-lap joints. *Journal of Composite Structures* 2006; 72:119–29.
- [**LJF-1**] Le Joint Français, PR 1782 C Mastic d'étanchéité réservoirs structuraux interposition faible densité, Édition 10/2011
- [**MEU-1**] L. Meunier et al. Caractérisation du comportement mécanique d'élastomères silicones chargés et non chargés. 18ème Congrès Français de Mécanique, Aug 2007, Grenoble, France. hal-01978979
- [**MOO-1**] M.A. Mooney. A theory of large elastic deformation. *Journal of Applied Physics*. 1940; 11(9):582-592.
<http://dx.doi.org/10.1063/1.1712836>.
- [**MOR-1**] D.C. Moreira, L.C.S. Nunes, Comparison of simple and pure shear for an incompressible isotropic hyperelastic material under large deformation, *Polymer Testing* 32 (2013) 240–248
- [**NIU-1**] Michael .C.Y. Niu. *Airframe Structural Design*
- [**OGD-1**] R.W. Ogden. Large deformation isotropic elasticity on the correlation of theory and experiment for the incompressible rubber-like solids. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*. 1972; 326(1567):565584.
- [**PAR-1**] E. Paroissien, F. Lachaud et al. Simplified stress analysis of hybrid (bolted/bonded) joints, *International Journal of Adhesion and Adhesives* 77 (2017) 183–197
- [**PAR-2**] Paroissien, E. Modélisation simplifiée des transferts d'effort dans les assemblages boulonnés et/ou collés, *Mémoire d'Habilitation à Diriger des Recherches, Université de Toulouse III Paul Sabatier (FR)*. (2020)
- [**RIV-1**] R.S. Rivlin. Large elastic deformations of isotropic materials VII. Experiments on the deformation of rubber, *Philosophical Transactions of the Royal Society of London A*. (1951) 243(865), pp. 251-288.
- [**ROS-1**] P.L. Rosendahl, *From Bulk to Structural Failure: Fracture of Hyperelastic Materials* (2020)
- [**SAS-1**] M. Sasso, G. Palmieri, G. Chiappini, D. Amodio, Characterization of hyperelastic rubber-like materials by biaxial and uniaxial stretching tests based on optical methods, *Polymer Testing* 27 (2008) 995–1004
- [**SHA-1**] M. Shahzad et al. Mechanical Characterization and FE Modelling of a Hyperelastic Material, *Materials Research*. 2015; 18(5): 918-924.
- [**WIL-1**] M. L. Williams, Structural analysis of viscoelastic materials, *AIAA Journal* (1964) vol 2: 785-808