

ICSAAM 2018 - August 30th Modelling the shape of an adhesive joint during assembly

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Context



- **S3PAC** project (Simulation and Supervision System for the production of bonded assemblies)
 - FUI 21 project
 - Co-funded by BPI france, the Occitanie region and the Aquitaine region



- Objectives:
 - Improve the mechanical performance of the assemblies with the use of adhesive [Paroissien 2006]
 - Propose a bonding process and ensure both the reliability and the reproductibility
 - Simulation of the assembly process:
 - Model the shape of the adhesive bond
 - Predict the flaws





Prospective assembly process





Assembly

End of assembly









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Adhesive



- SAF 30 MIB [AEC Polymers] AECPOLYMERS
 - Methacrylate structural adhesive
 - Bi-component

Component	Density
Adhesive (90%)	1,01 – 1,05
Hardener (10%)	1,10 – 1,15



Curing occurs during the process

- Time dependant physico-chemical properties
- Initial viscosity gradient depending of the deposit duration
- Process duration also affects rheology

Beads of SAF 30 MIB





Presentation outline



- Context
- Rheology
- Numerical simulation
- Preliminary experience and comparison with the simulation
- Conclusion





Experimental Characterization

ental

Preliminary

comparison

• Parallel plates rheometer

Rheology

 Frequency sweep between 100 Hz and 1 Hz

Simulation

- Herschel-Bulkley model
 - Viscoplastic behaviour with the adhesive not flowing before attaining the yield stress au_0
 - Previously used to describe adhesives [Bergamasco 2014]



Characterization of the dynamic viscosity (100 Hz at the bottom, 1 Hz at the top)

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Conclusion





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Mathematical method

Preliminary

comparison

• Finite Volume Method (FVM)

[Patankar 1980]

Rheology Simulation

- Implemented in OpenFOAM 5.x a C++ open source CFD toolbox
- Discretization of the transport equation of a field ϕ in a control volume using Gauss's theorem

$$\int_{V_p} \frac{\partial \rho \phi}{\partial t} dV + \int_{V_p} div(\rho \phi \vec{u}) dV - \int_{V_p} div(\rho \Gamma \overrightarrow{grad} \phi) dV = \int_{V_p} S_{\phi} dV$$



Conclusion

Polyhedral FVM discretization [Berberović 2009]

• Volume Of Fluid method (VOF) for tracking the interface

of the adhesive [Rusche 2002]

Uses a modified transport equation to calculate γ (volume fraction of phase) [Berberović 2009] :

 $\frac{\partial \gamma}{\partial t} + div(\overrightarrow{u_{adhesive}\gamma}) + div((\overrightarrow{u_{adhesive}} - \overrightarrow{u_{air}})\gamma(1-\gamma)) = 0$

coupling classical VOF and a two-fluid Eulerian model

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Preliminary experimental Conclusion

comparison



Computational method

Simulation

• Temporal discretization by a Crank-Nicolson Scheme

Rheology

- Pressure-velocity coupling based on PISO (pressure implicit with splitting of operators)
- Adaptative time step controlled by the Courant number (<1) [Berberović 2009]

$$Co = \frac{|\overrightarrow{U_f} \cdot \overrightarrow{S_f}|}{\overrightarrow{PN} \cdot \overrightarrow{S_f}} \Delta t^2 < 1$$

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Boundary conditions

Parameter Surface	Velocity	Pressure	Phases
Upper plate	No slip	$ec{ abla} p = ec{0}$	$ec{ abla}\gamma=ec{0}$
Lower plate	No slip	$\vec{\nabla} p = \vec{0}$	$\vec{\nabla}\gamma = \vec{0}$
atmosphere	$\vec{\nabla} u = \vec{0}$	0 Pa	$ec{ abla}\gamma=ec{0}$
	U _{docking} = 1 mm/s atmosphere		7
unosphere Form	Bead 1 er plate er plate	Bead 2	atmosphere

atmosphere







Beads rheological parameters

	Bead 1 : t _{1c} = 6,76 min	Bead 2 : t _{2c} = 1,725 min
$ au_0$ (Pa)	506,20	247,37
λ (Pa.s)	102,58	65,77
n	0,5786	0,5786

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Experimental beads layout



 Beads characteristics at the start of the compression

	Bead 1	Bead 2
Weight	1,22 g	0,73 g
Elapsed time after deposit	6,76 min	1,725 min

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Rheology Simulation







Final bond thickness : 1 mm; t = 0 s



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Rheology Simulation







Final bond thickness : 1 mm; t = 3,5 s



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Final bond thickness : 1 mm; t = 5 s



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Rheology **Simulation** Preliminary experimental Conclusion comparison







Final bond thickness : 1 mm; t = 6 s



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Final bond thickness : 1 mm; t_{final} = 7 s



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Preliminary experimental testing

Preliminary experimental

comparison

• Objectives:

Rheology Simulation

- Confront simulation results with reality
- Find weaknesses of the numerical modelling
- First compression test performed using a traction-compression machine:
 - Compression velocity of 1 mm/s
 - Plexiglas plates
 - Upper plate is fixed to the mobile crossbeam of the machine
 - Final distance between the plate is 1 mm



Conclusion

Preliminary experimental setup



Experimental Beads layout

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Initial shape comparison

Shape of the before compression (t = 0 s) :**Experimental**Simulated





Comparison



Modelled beads : less width and length, more depth

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Final shape comparison

Shape of the joint immediately after compression (t_{final} = 7 s) :ExperimentalSimulatedComparison



Preliminary experimental comparison Rheology Simulation Conclusion



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Final shape comparison

Shape of the joint immediately after compression ($t_{final} = 7 s$): **Experimental** Simulated Comparison



Rheology Simulation **Preliminary** comparison



Compressive load comparison

• Compressive load measured on the upper plate of plexiglas

- Similar curve despite discrepancy between initial shapes
 - Discrepancy observable in the log-lin plot

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Conclusion

Prospects: investigate the reasons of the observed differences

- Rheology
 - Accurracy of the model
 - Non homogenous cure
- Simulation
 - Inacurate initial geometry
 - Subpar meshing

Rheology Simulation

Experimental uncertainities

- Possible presence of air bubbles in the joint
- Relevance of the no slip hypothesis at the plates

• Future work:

- Experimental testing
- Implementation of time dependant rheological model
- Simulation of manufacturable geometries
- Iso advector (référence)
- Comparison of bond shape using X-ray tomography





Thank you for your attention





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Annex 1 – Volume of fluid method (VOF)



- The volume of fluid method (VOF) to track the interface of the adhesive in the air is used
- For a phase, the following equations are simultaneously resolved:
 - the continuity equation :
 - $div(\vec{u}) = 0$
 - the momentum equation :

$$- \frac{\partial \rho \vec{u}}{\partial t} + \rho (\overline{grad} \cdot \vec{u}) \vec{u} = -\overline{grad}(p) + div (\overline{\overline{T}}) + \rho \overrightarrow{f_b}$$

• a modified transport equation:

$$- \quad \frac{\partial \gamma}{\partial t} + div(\overrightarrow{u_{adhesive}}\gamma) + div((\overrightarrow{u_{adhesive}} - \overrightarrow{u_{air}})\gamma(1-\gamma)) = 0$$

- Coupling classical VOF and a two-fluid Eulerian model
- Gives a better interface resolution according to Berberović et al. (2009) [3]
- Where \vec{u} is the velocity field shared by both phases
- γ the phase fraction
- $\overline{\overline{T}}$ the viscous stress deviatoric, $\overline{\overline{T}} = 2\eta \overline{\overline{\varepsilon}} 2\eta div(\vec{u}) \frac{\overline{I}}{3}$
- $\overrightarrow{f_b}$ a mass load
- and *p* the pressure





Annex 2 – VOF - Interface capturing algorithm



• From the following transport equation in the VOF method :

 $\frac{\partial \gamma}{\partial t} + div(\overrightarrow{u_{adhesive}\gamma}) + div((\overrightarrow{u_{adhesive}} - \overrightarrow{u_{air}})\gamma(1-\gamma)) = 0$

- Multi-dimensional Universal Limiter with Explicit Solution (MULES) [Deshpande 2012], [Raees 2011]
 - Limit the higher order calculation at the interface between phases
 - The artificial compression term is calculated only at the interface
 - Reduction of the computational cost
 - Reduction of the numerical diffusion at the interface



Annex 3 – Solution procedure



- PIMPLE = Merged PISO SIMPLE (respectively standing for Pressure-Implicit-Split-Operator, and Semi-Implicit-Method-Of-Pressure-Linked-Equations)
- Based on the PISO algorithm, a segregated pressure-based solver to calculate the velocity and pressure fields [Rhie and Chow, 1982]
- The « outer » correction loops aim to ensure the convergence of explicit terms in equations [Holzmann 2017]







Annex 4 – Analytical study



Analytical comparison - 1

- Rheology :
 - Herschel-Bulkley model:

 $\tau = \tau_0 + \lambda \dot{\gamma}^n$

 τ_0 = 372,9 Pa; λ = 257,3 Pa.s; n = 0,324 [Bergamasco 2014]

- Viscoplastic behaviour with the adhesive not flowing before attaining the yield stress τ_0
- Previously used to describe adhesives [Engmann 2005]
- Analytical law [Bergamasco 2014]
 - Compression load for a cylinder:

$$F = \sigma_0 A + \frac{2RA}{3H}\tau_0 + \frac{2RA\lambda}{(n+3)H} \left(\frac{2n+1}{n}\right)^n \left(\frac{LV_h}{H^2}\right)^n$$



R(t=0)	15 mm
R _{max}	30 mm
H(t=0)	5 mm
Vh	0,1 mm/min
Duration of	40 s
compression	
Final thickness of	1 mm
the bond	





Annex 4 – Analytical study - 2



Analytical comparison -2

- Quasi-2D axisymmetric simulation
- Incompressible fluid



Compressive load over time



- Good fit between analytical and numerical results
- Max error : 10% at the end





Annex 4 – Analytical study - 2



Analytical comparison -2

- Quasi-2D axisymmetric simulation
- Incompressible fluid



Compressive load over time



- Good fit between analytical and numerical results
- Max error : 10% at the end





Annex 4 – Analytical study - 2



Analytical comparison -2

- Quasi-2D axisymmetric simulation
- Incompressible fluid



Compressive load over time



- Good fit between analytical and numerical results
- Max error : 10% at the end





Annex 5 – Identification of rheological parameters



 $|\eta^*(\omega)| = \eta(\dot{\gamma})$



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[Cox 1958] Compressive load over time $\int_{10^{-2}}^{10^{-2}} \int_{2}^{10^{-2}} \int_{10^{-2}}^{10^{-2}} \int_{10^{-$

Cox-Merz rule:

Compressive load over time



Annex - references



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