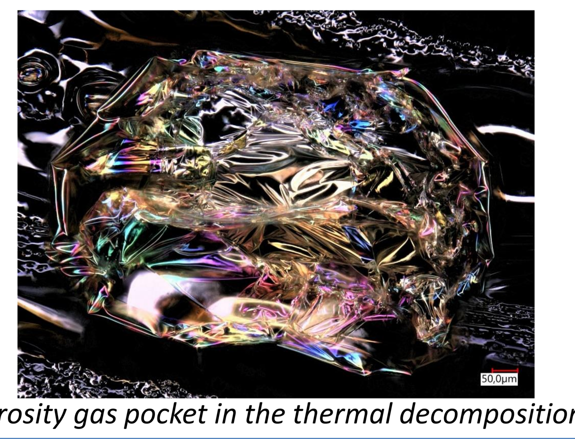
Numerical modelling of porosity formation in thermoplastic composites undergoing thermal decomposition at high temperatures

David Philippe, Benoit Vieille and Fabrice Barbe
Normandie Univ, INSA Rouen, UNIROUEN, CNRS, GPM, 76000 Rouen, France
Contact : david.philippe@insa-rouen.fr

Context and objectives

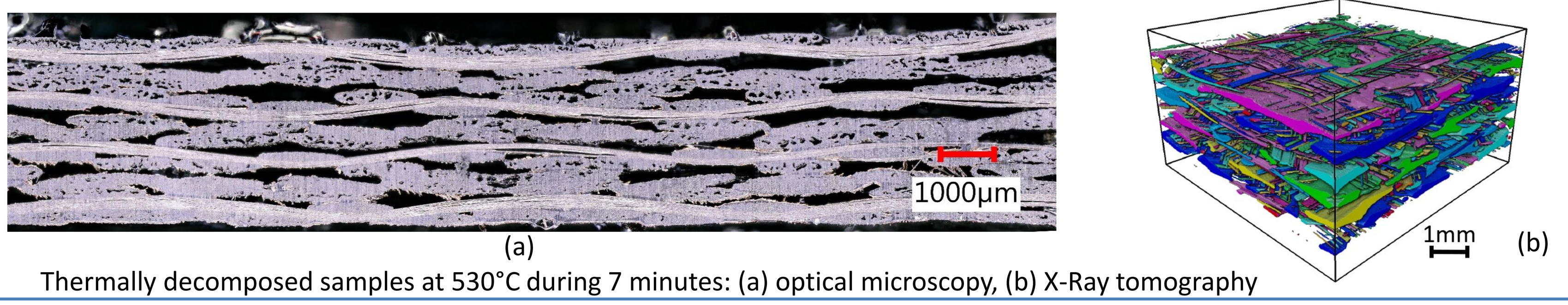
- Study the resistance to fire of aeronautical composite structural parts [1,2]
- Experimental investigation of C/PPS laminates thermal decomposition through time and for different temperatures (up to 600°C)
- Create a meso-structure based FE model of the laminates:
  - Identify and quantify the porosity formation
  - Explicitly represent the transformation of matrix elements into porosities
- Model the influence of porosity formation on the thermo-mechanical behavior under thermal aggression (high temperature or flame exposure)



Typical porosity gas pocket in the thermal decomposition regime

Experimental setup

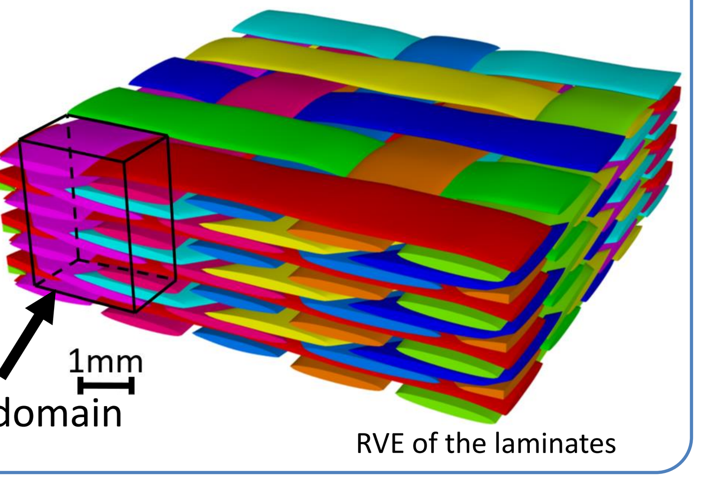
- Thermal decomposition of samples under isothermal conditions (furnace)
- Geometry and mass measurements to determine the porosity content
- Optical microscopy / X-ray tomography to evaluate the space distribution of porosities



Thermally decomposed samples at 530°C during 7 minutes: (a) optical microscopy, (b) X-Ray tomography

Numerical setup

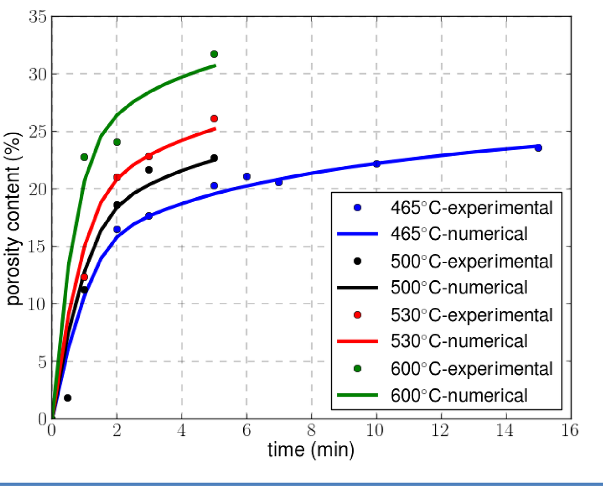
- Explicit yarn/matrix representation FE model
- 1/28th of RVE (1.7x1.03x2.2mm^3)
- 5,000,000 elements
- Thermo-mechanical properties (yarn & matrix) from [3]
- QI: quasi-isotropic lay-up

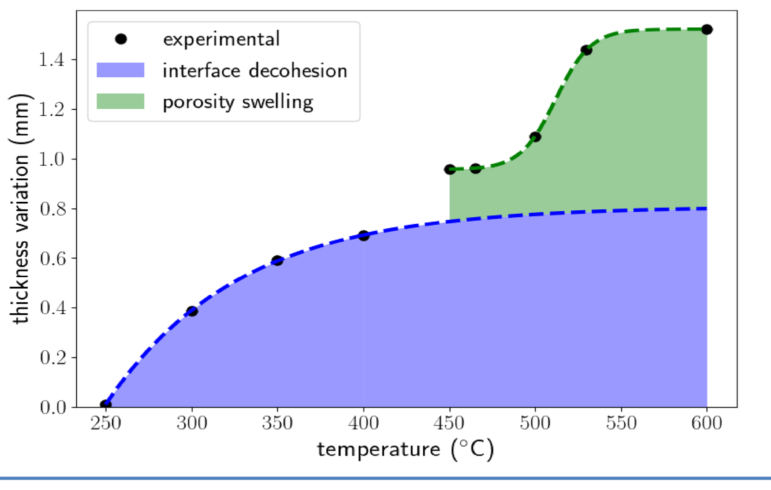


RVE of the laminates

Experimental results and identification of the model

- 3 porosity formation mechanisms:
  - ① • Nucleation → probabilistic law p(t,T,Δt) governing the porosity formation
  - ② • Growth / coalescence → impact of local porosity volume fraction on p(t,T,Δt)
  - ③ • Yarn / matrix interface decohesion
- Significant porosity-induced swelling: ① & ②→ internal pressure within the porosities
  ③→ cohesive elements (work in progress)
- Porosity formation at the end of each time increment Δt
- Structural damage to yarn integrity for t>5min and T>500°C → modelling limitations





Nucleation kinetics model

The porosity volume fraction η_p solution of the differential equation:

$$\dot{\eta_p}(t,T) = G(t,T)\left(1-\eta_p(t,T)\right) \quad \text{where} \quad G(t,T) = \frac{p(t,T,\Delta t)}{\Delta t} \xrightarrow[\text{for constant } \Delta t \text{ at increment k}]{\text{closed form}} \eta_p(k\Delta t) = \sum_{i=1}^{k}(-1)^{i+1}\sum_{c\in C_{i,k}}\prod_{j\in c}p_j$$

with $C_{i,k}$ the set of possible combinations of i elements out of k

Parameter identification

$$G(t,T) = \frac{\tau_1 + \tau_2\left(\frac{T-T_d}{T_{ref}-T_d}\right)^b}{t+\tau_3}$$

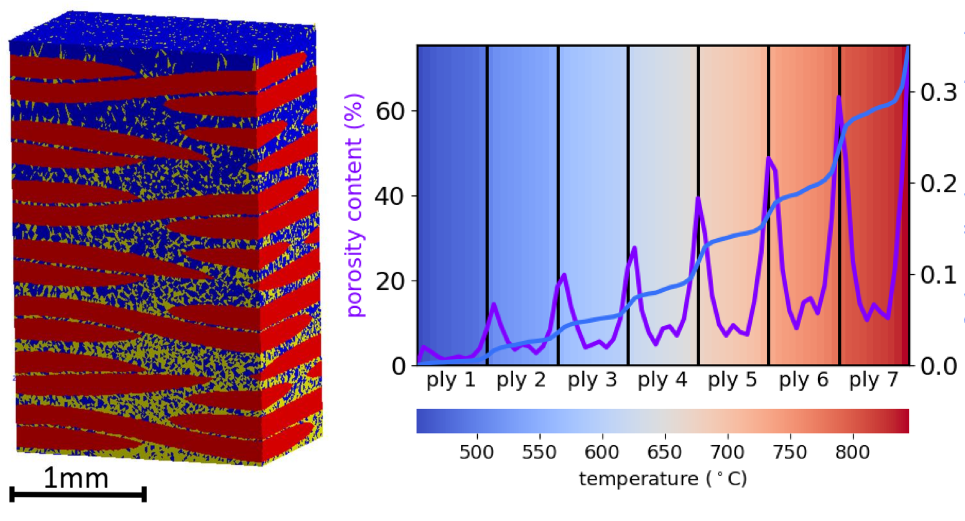
+ Identification using Euler's scheme and optimization

Parameter	Unit	Value	Main role
τ_1	No unit	0.205	Affects G for $T = T_d$
τ_2	No unit	0.139	Dependance of G to T
τ_3	Time (s)	15.0	Time shift at the initial time
b	No unit	1.15	Dependence of $\frac{\partial G}{\partial T}$ to T
T_{ref}	°C	530.0	Intermediate temperature

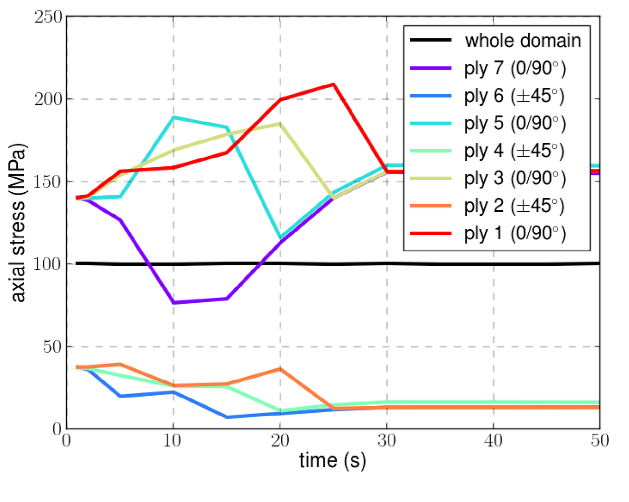
Coupled flame / mechanical modelling

- Heat flux imposed on the upper surface
- Radiation and convection on the back surface

→ Example of a 116kW/m² heat flux



Example after 90s: swollen laminates / thermal decomposition state



Axial stress distribution

Conclusions and perspectives

- ✓ Numerical modelling of the time and temperature influence on the porosity content, the nucleation and growth mechanisms and the induced swelling
- ✓ The model has been used to predict the porosity distribution resulting from a thermal aggression and to simulate the loading capabilities of the decomposed sample
- Interface decohesion consideration through cohesive elements will be pursued
- Further characterization of the mechanical behavior will be carried out and compared with numerical results to study the thermomechanical coupling

References:

[1] Y. Carpier, A. Alia, B. Vieille, and F. Barbe. "Experiments based analysis of thermal decomposition kinetics model. Case of carbon fibers PolyPhenylene Sulfide composites". *Polymer Degradation and Stability*, Vol. 186, 2021.

[2] Y. Carpier, B. Vieille, A. Coppalle, and F. Barbe. "Study of thermomechanical coupling in carbon fibers woven-ply reinforced thermoplastic laminates: tensile behavior under radiant heat flux". *Polymer Composites*, Vol. 41, pp. 3552–3563, 2020.

[3] Y. Carpier, B. Vieille, F. Barbe, and A. Coppalle. "Meso-structure-based thermomechanical modelling of thermoplastic-based laminates subjected to combined mechanical loading and severe thermal gradients". *Composites Part A: Applied Science and Manufacturing*, Vol. 162, pp. 107-165, 2022