ONERA

THE FRENCH AEROSPACE LAB

24èmes journées du GDR FEUX

DGA Techniques Aéronautiques

Comportement au feu des structures composites aéronautiques

Etat de l'art et attentes

MADMAX

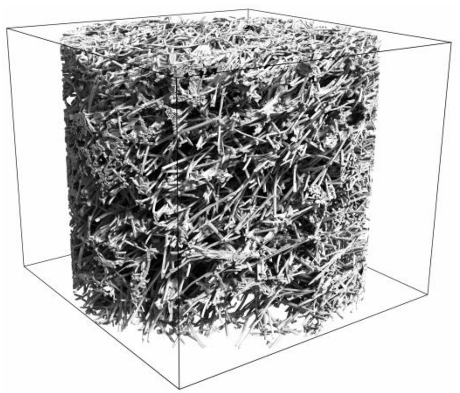
phy sics of fire

FUTURE SKY SAFETY

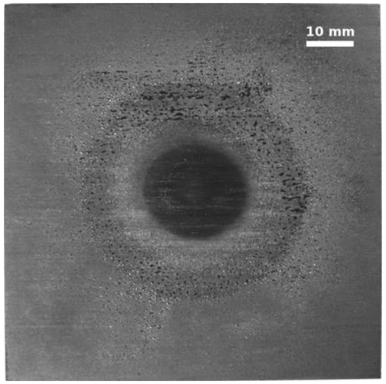
Context and fundamental issues

Fire behaviour of composite materials

Multi-scale problem



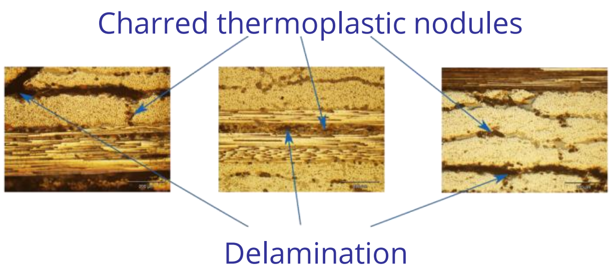
X-ray µtomography, Panerai @NASA



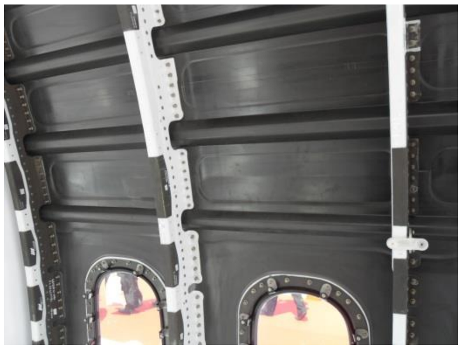
Laser-induced decomposition of a composite test coupon

Length scale

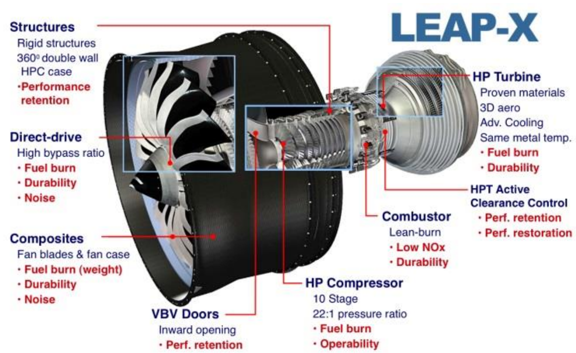
Condensed matter	Material	Structure	Aircraft/Engine
[mg - mm]	[g - cm]	[kg - m]	[t - m]



Influence of the charring nodules on the onset of delamination damage



Frame/Skin/Stringer hybrid junctions



Context and fundamental issues

Fire behaviour of composite materials

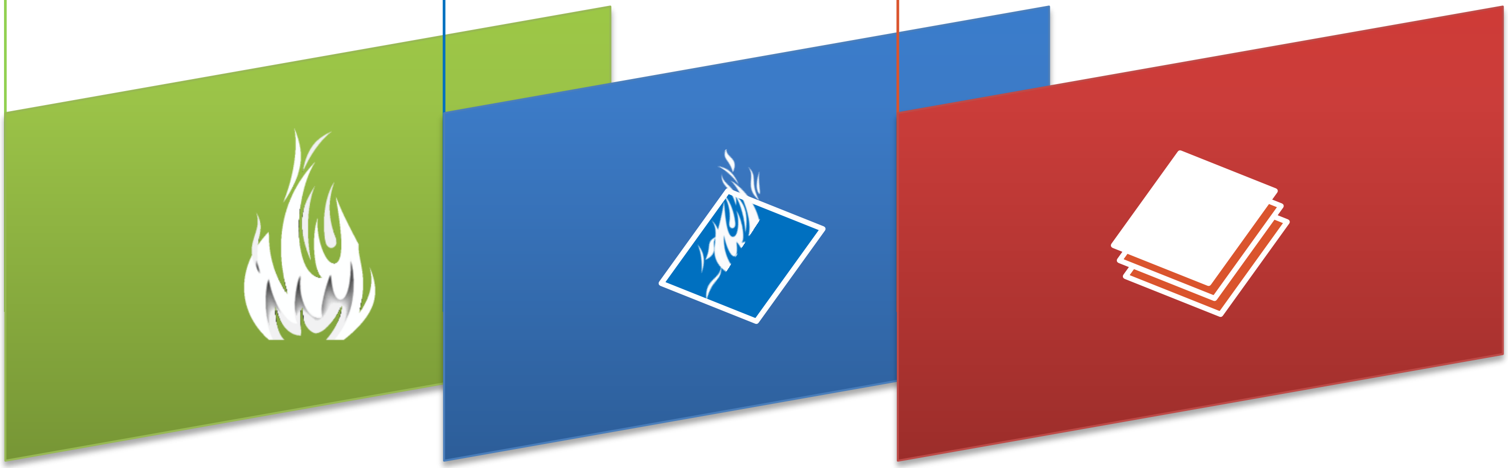
Multi-physics problem with coupled phenomena

STATE OF THE ART

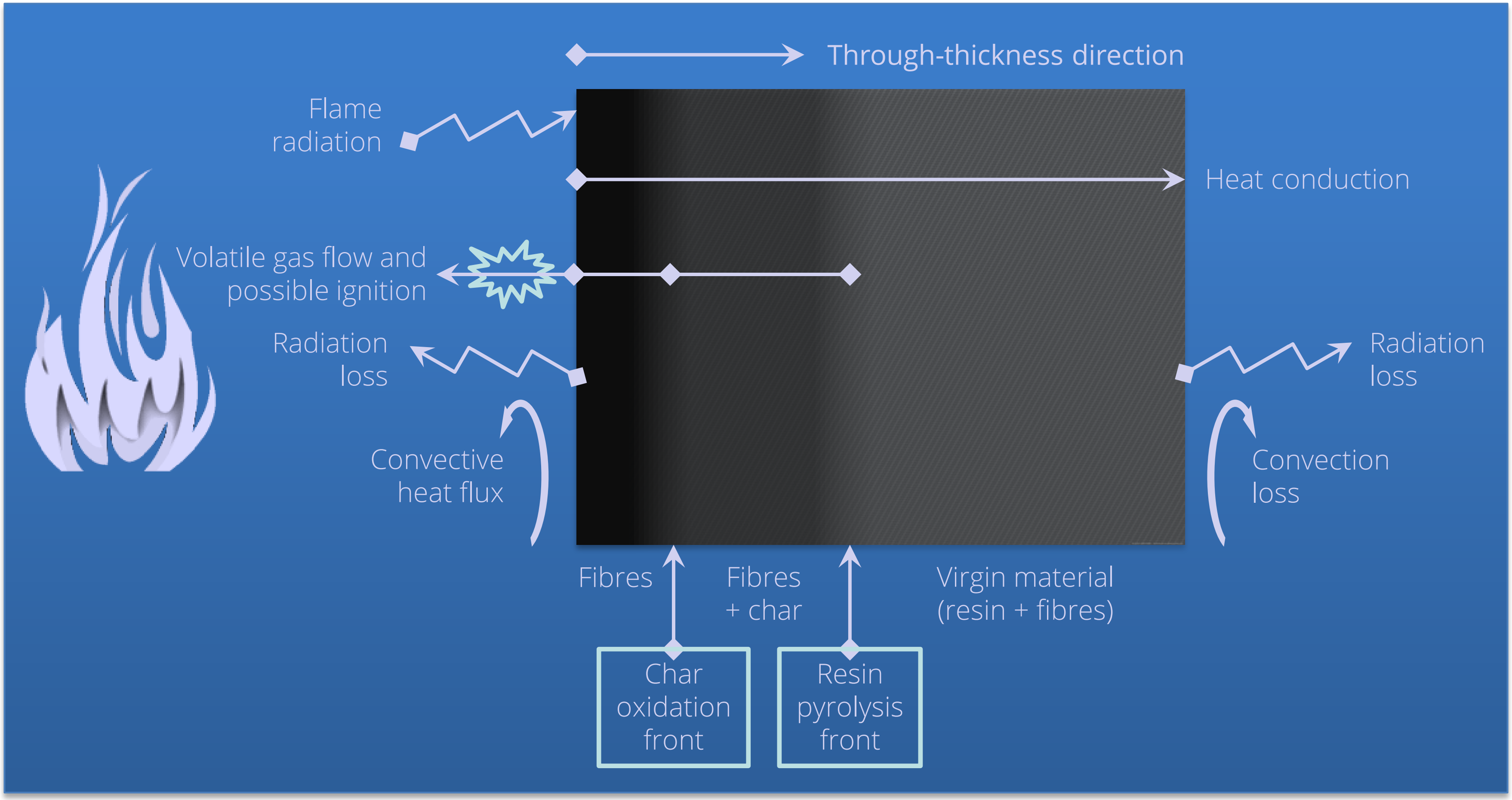
Fire
- Fluid dynamics
- Two-phase flows
- Premixed or diffusion flames

Interface
- No coupling
- Constant heat flux
- Convection/radiation loss

Composite
- Orthotropic heat transfer
- Pyrolysis
- Darcy's flow within porous medium
- Thermal expansion



Physical processes during polymer composite decomposition *



* Review of fire structural modelling of polymer composites
A.P. Mouritz et al. **Composites: Part A 40 (2009) 1800-1814**

Context and fundamental issues

Fire behaviour of composite materials

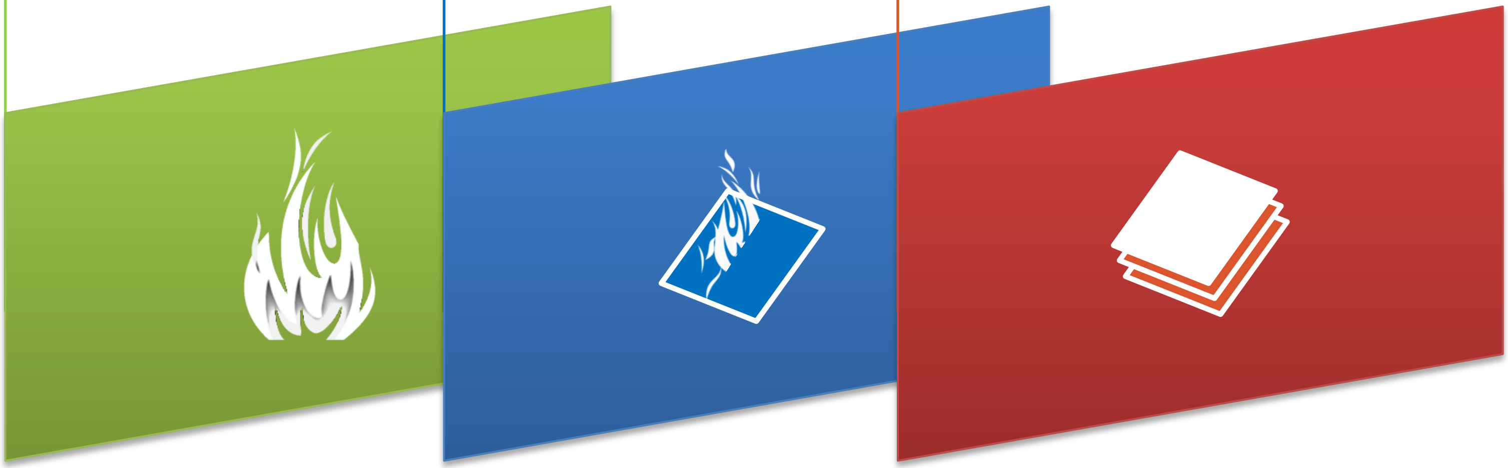
Multi-physics problem with coupled phenomena

STATE OF THE ART

Fire
- Fluid dynamics
- Two-phase flows
- Premixed or diffusion flames

Interface
- No coupling
- Constant heat flux
- Convection/radiation loss

Composite
- Orthotropic heat transfer
- Pyrolysis
- Darcy's flow within porous medium
- Thermal expansion



NEXT STEPS

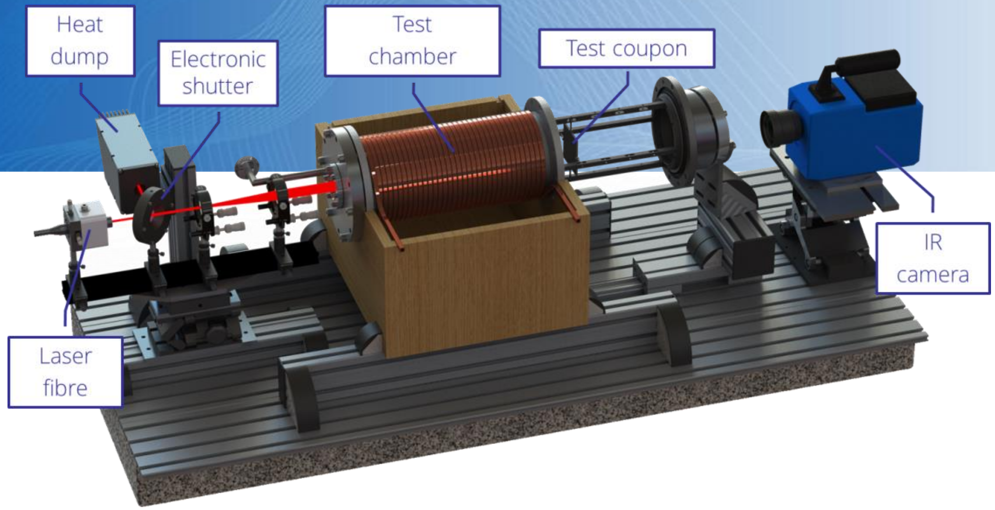
Relevant fire dynamics
- Large scale (pool) fires
- Soot residues and radiation
- Turbulence and subgrid scale models
- Accurate wall heat flux prediction

Surface couplings
- Heat flux space and time distribution
- Pyrolysis volatiles ignition
- Deformation/Ablation
- Friction due to surface roughness

Volume couplings
- Thermal behaviour
- Mechanical behaviour
- Delamination onset and growth
- Heat and mass transfer within cracked medium

BLADE facility

Banc **L**aser de c**A**ractérisation et de **DE**gradation



blade

fire

inject

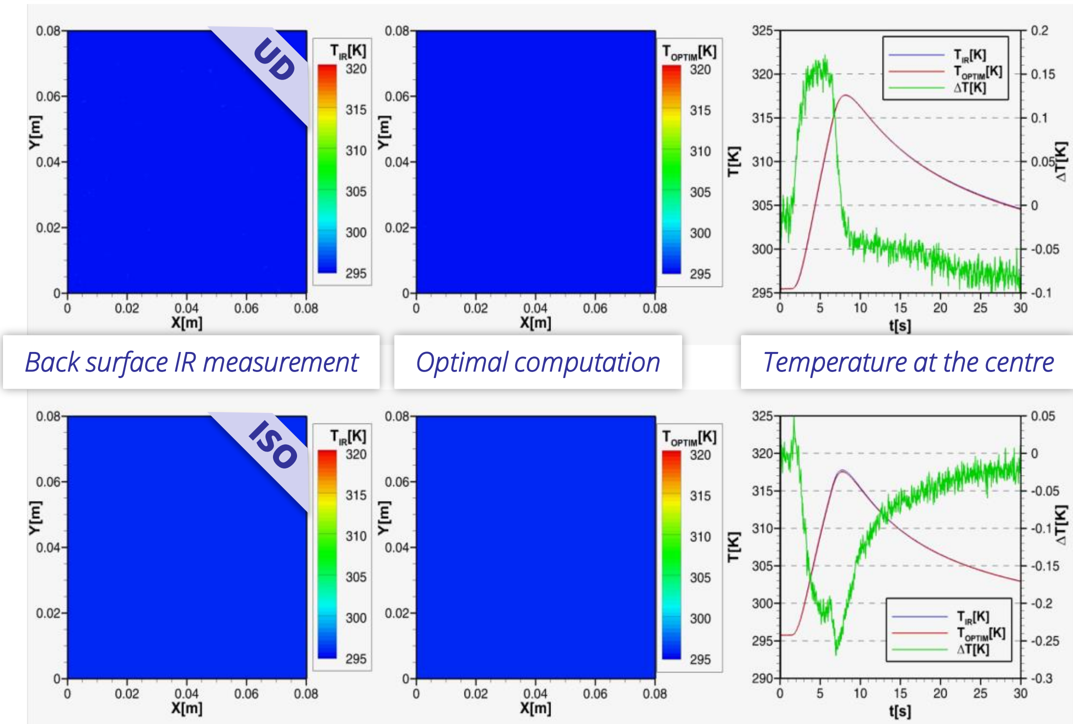
modethec

adethec

ONERA CEDRE

ONERA ZEBULON

Anisotropic thermal properties assessment

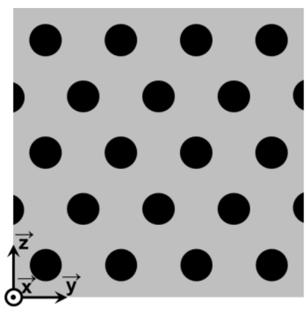


BLADE facility

Banc **L**aser de c**A**ractérisation et de **DE**gradation

Homogenisation of the thermal properties

REV



- matrix
- fibres

VIRGIN

- *resin*
- *gas**

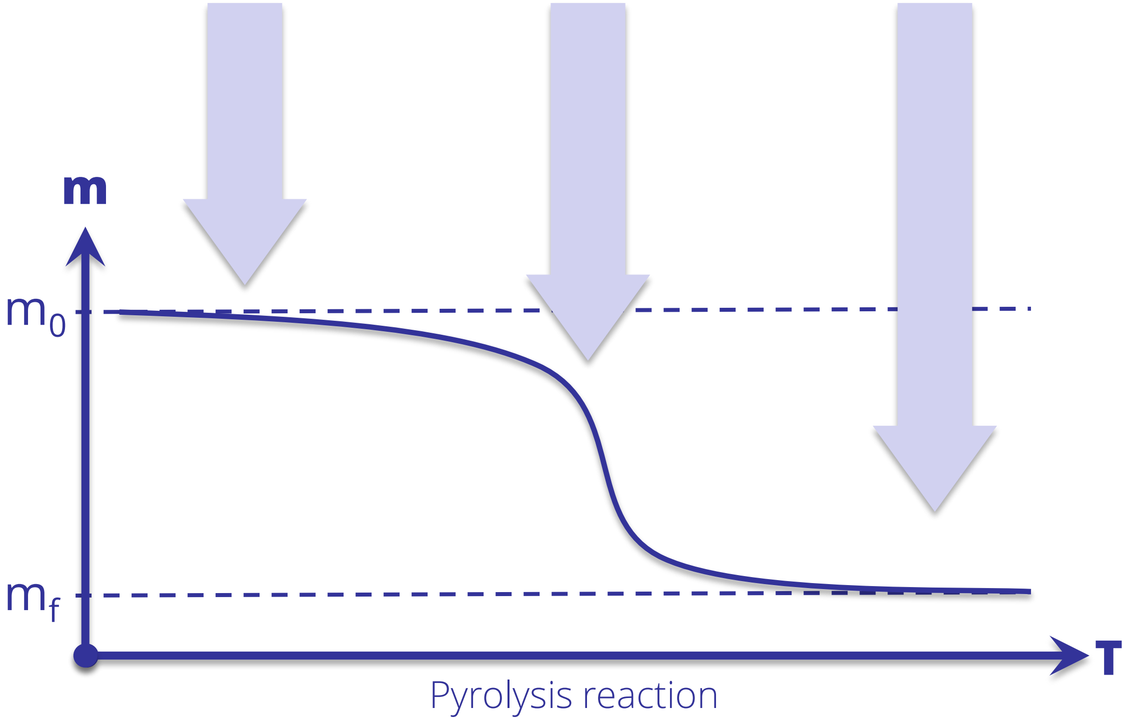
*(*initial porosity)*

CHARRING

- *resin*
- *char*
- *gas(es)*

CHARRED

- *char*
- *gas(es)*



Thermal properties at the virgin state

Bridging functions using homogenisation theory

Thermal properties at the charred state

BLADE facility

Banc **L**aser de c**A**ractérisation et de **DE**gradation

blade

fire

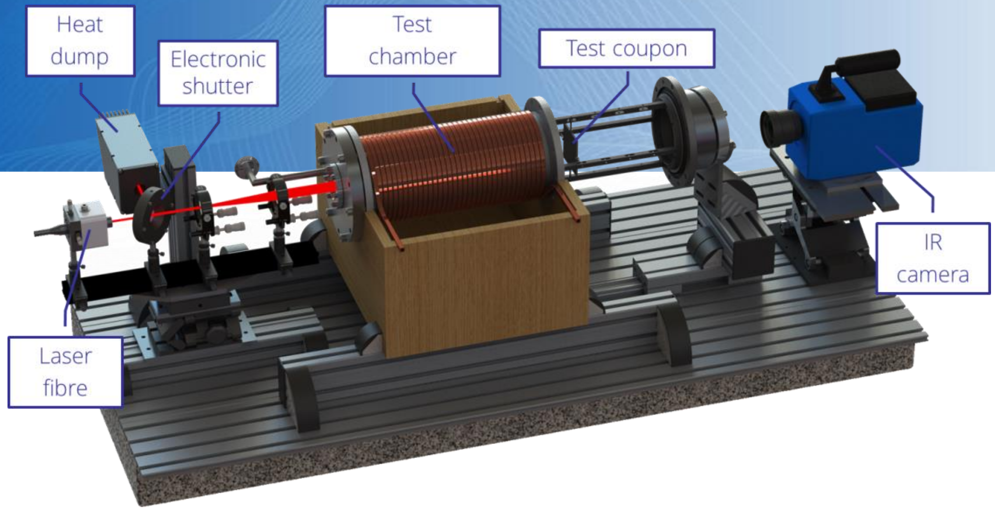
inject

modethec

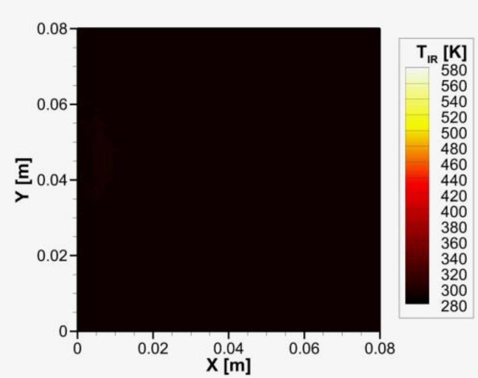
adethec

ONERA CEDRE

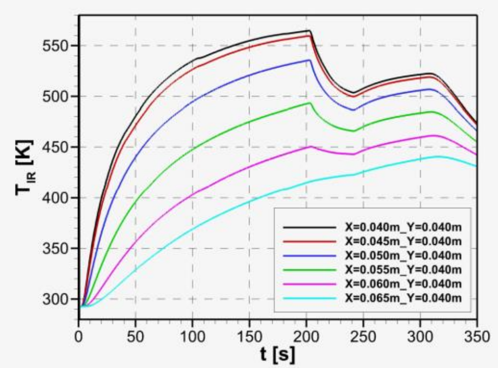
ONERA ZEBULON



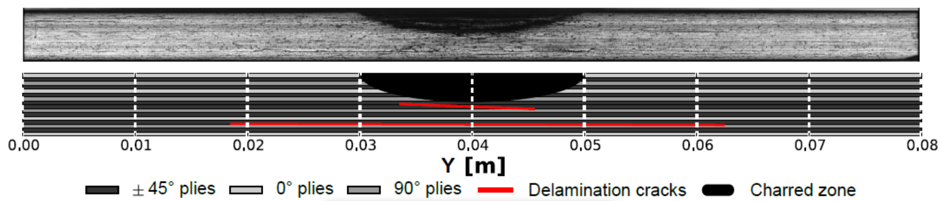
Laser-induced decomposition



Temperature evolution on the back surface



Back surface IR measurements



Micrographic analysis

phyFire

* Damage analysis for thermal loading induced by laser impact in epoxy composite laminate
C. Huchette, G. Leplat Et V. Biasi **ECCM17 (2016)**

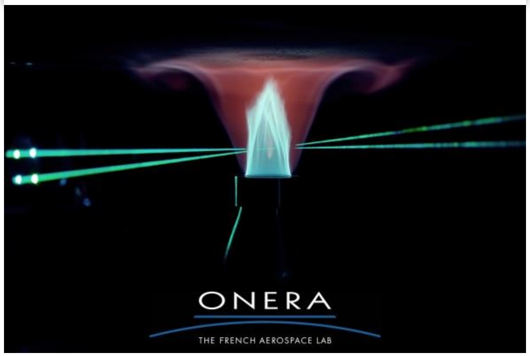
ONERA
THE FRENCH AEROSPACE LAB

FIRE facility

Flame-wall **I**nteraction **R**esearch **E**xperiment

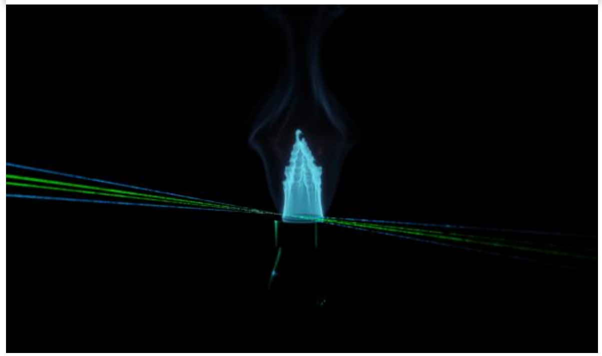
Thermal response
during fire-induced decomposition

Interaction between fire and composite materials



- *Test coupon size: 350 x 350mm*
- ***Premixed air-propane burner** Ø40mm*
- *Exposure time controlled by moving the burner on a sliding rail*
- *Transient temperature maps measured on the back surface using **IR thermography***
- *Deformation measured by **DIC** using 2 cameras in a stereoscopic configuration associated to high power LED projector of a 50% random pattern*
- ***Mass loss** assessed with a high precision weighing module (full scale $410\ g$, $\Delta m = 0.1\ mg$)*
- ***Flame front** visualisation using hydroxyl (OH) radicals emission in the UV spectrum*
- *Characterisation of the **flame dynamics** using Laser Doppler Velocimetry (**LDV**) and Particle Image Velocimetry (**PIV**)*

LDV measurement of flame dynamics



INJECT facility

INternal **J**oule heating for th**E**rmo me**C**hanical charac**T**erization

blade

fire

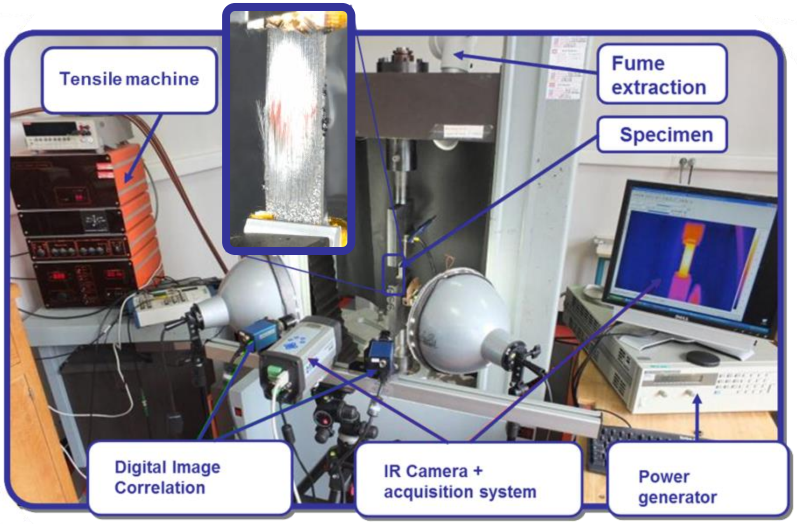
inject

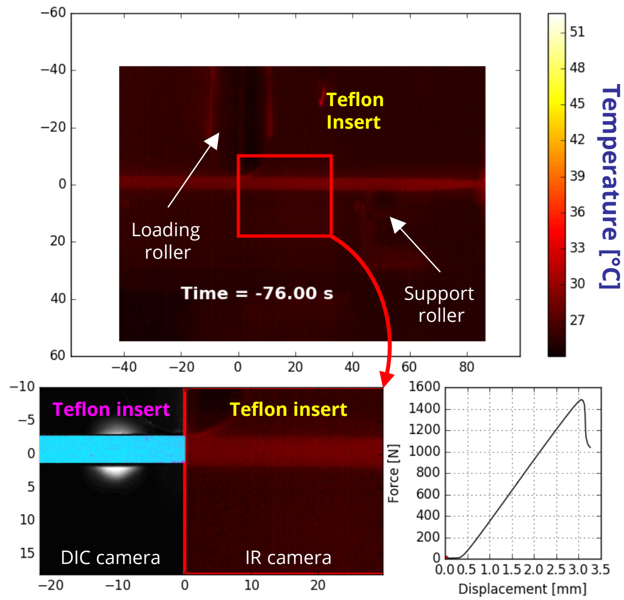
modethec

adethec

ONERA CEDRE

ONERA ZEBULON

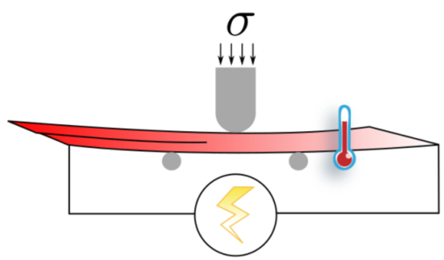




Features

- *Use Joule heating*
- *High heating rate*
- *Neglect the decomposition effect on the mechanical properties*
- *Multi instrumentation*
- *Characterisation in temperature of classical composite coupons*

Out of plane loading



D7905/D7905M – 14

MoDeTheC pryolysis solver

Modèle de **Dé**gradation **The**rmique des **C**omposites

blade

fire

inject

modethec

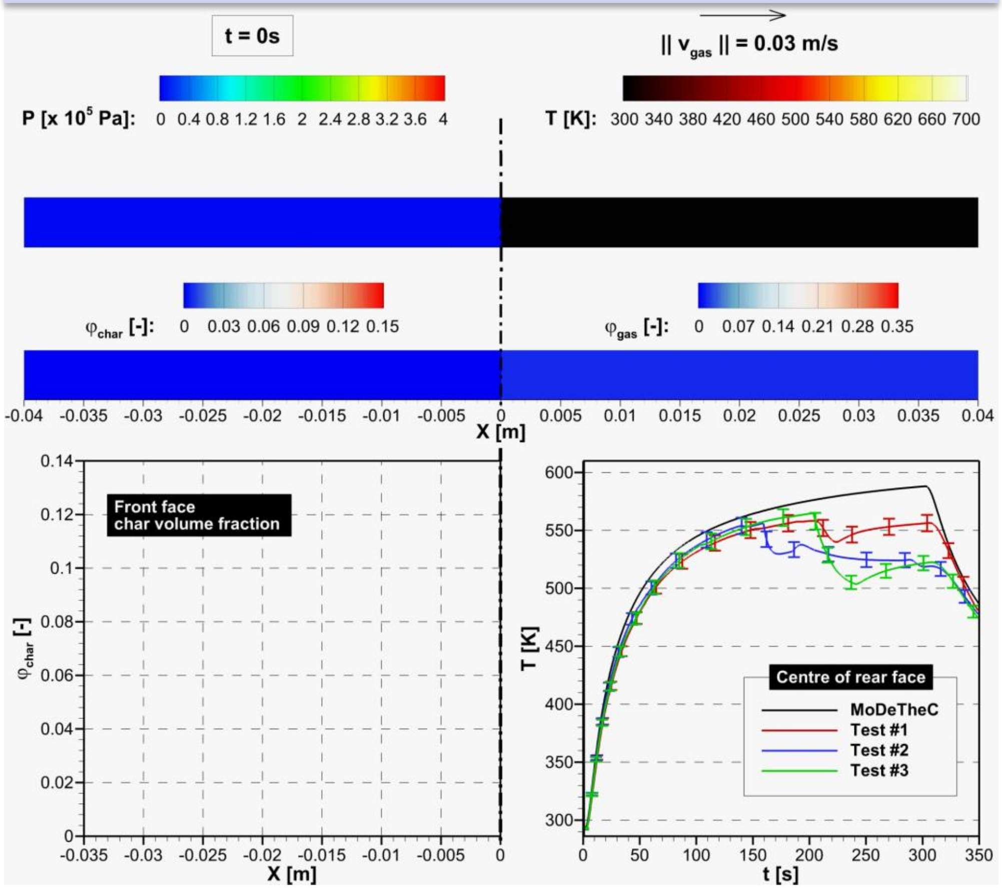
adethec

ONERA CEDRE

ONERA ZEBULON

Solver features

- Anisotropic heat and mass transfer
- Arrhenius reaction rate equations
- Multi-species formulation
- Darcy's flow of decomposition volatiles within the porous medium
- Mori-Tanaka homogenisation of the thermal conductivity tensor



phy sics of fire

* Modélisation thermique de la dégradation d'un matériau composite soumis au feu

V. Biasi. **PhD thesis, University of Toulouse (2014)**

ONERA THE FRENCH AEROSPACE LAB

ADeTheC post-processing toolbox

Analyse de la **Dé**gradation **The**rmique des **C**omposites

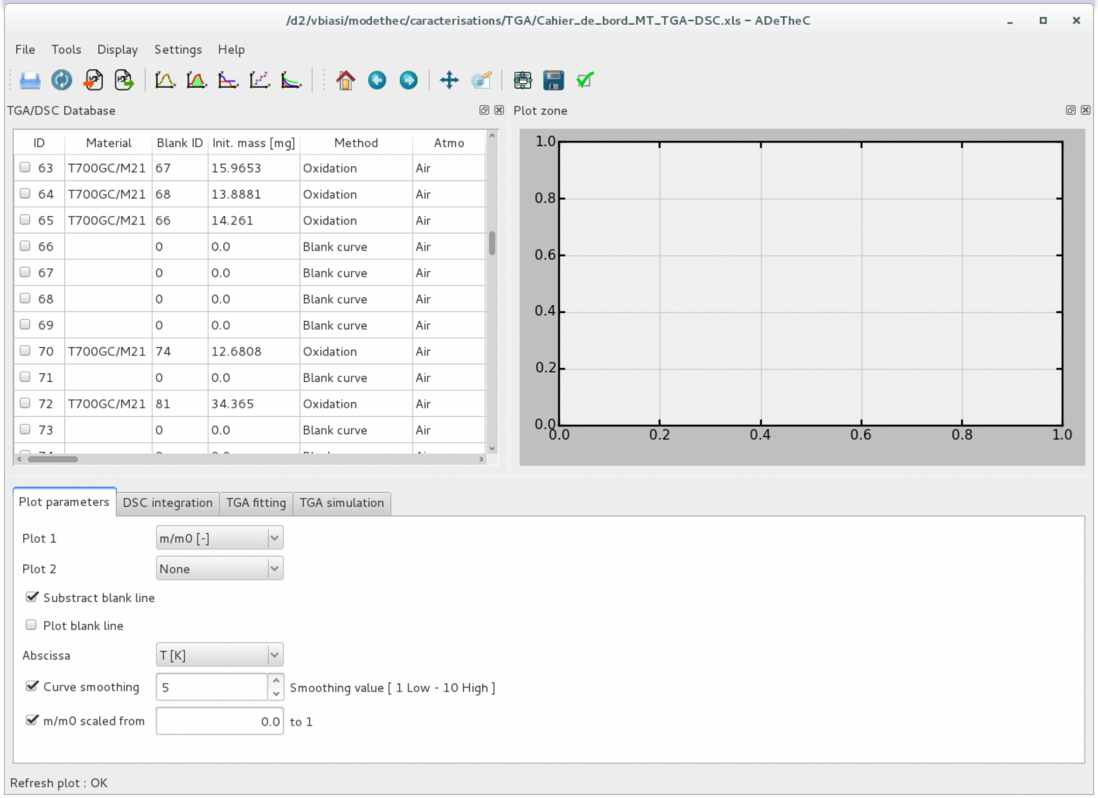
blade
fire
inject
modethec
adethec

ONERA CEDRE

ONERA ZEBULON

Toolbox features

- easy plot and data comparison of TGA and DSC measurements
- identification of Arrhenius parameters for chemical kinetics modelling of reaction rate equations
- user-defined multi-stage reaction mechanisms
- integration of DSC signals to extract the enthalpy of reactions
- reconstruction of species evolution as a function of temperature



CEDRE CFD multi-physics numerical suite

Calcul des **E**coulements **D**iphasiques **R**éactifs en **E**nergétique

blade

fire

inject

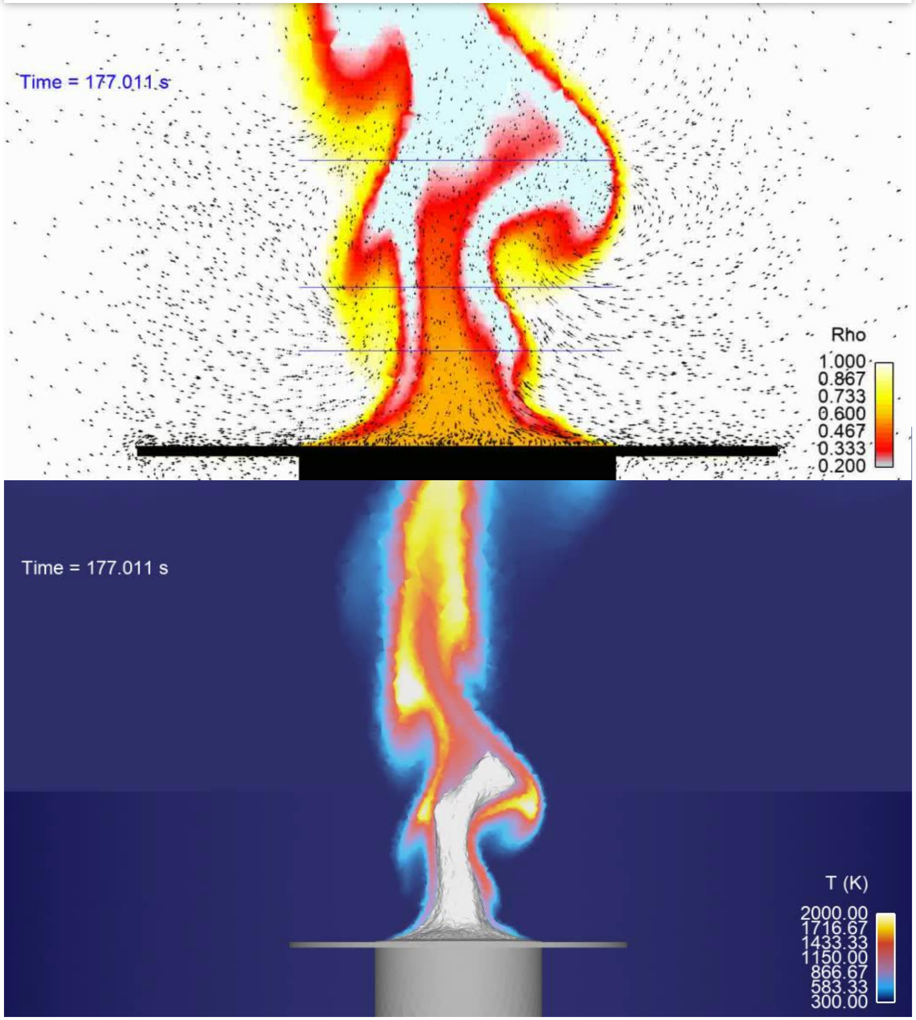
modethec

adethec

ONERA CEDRE

ONERA ZEBULON

FLAME (Fire Laboratory for Accreditation of Models by Experimentation)
@ SANDIA, Albuquerque, USA
3D large scale unsteady CH_4 pool fire simulation



Z-Set M&S analysis and simulation software

Zebulon non-linear finite-element solver

blade

fire

inject

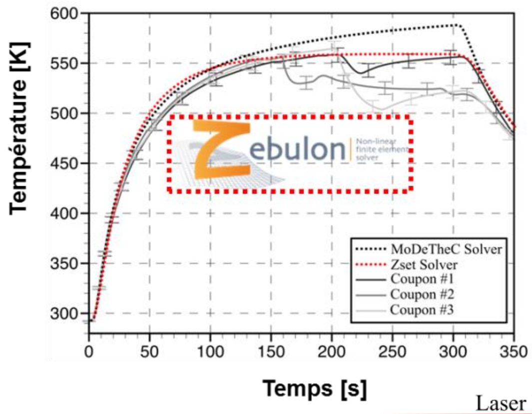
modethec

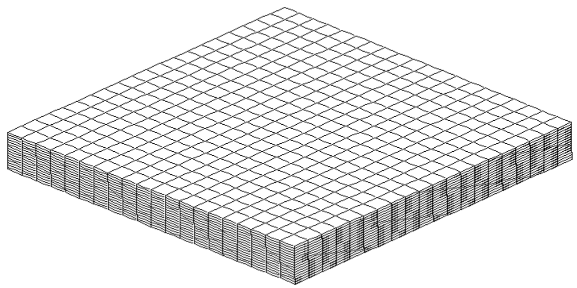
adethec

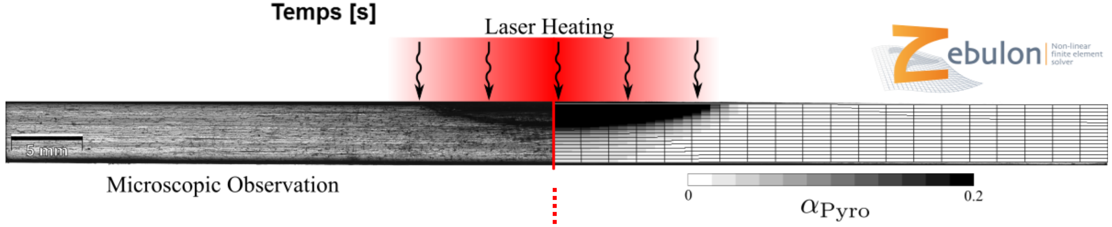
ONERA CEDRE

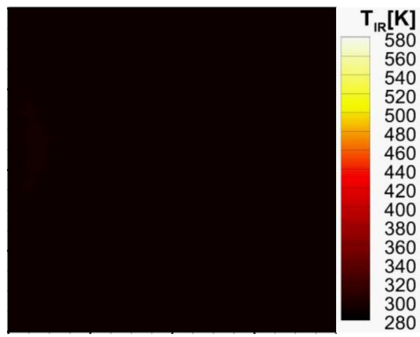
ONERA ZEBULON

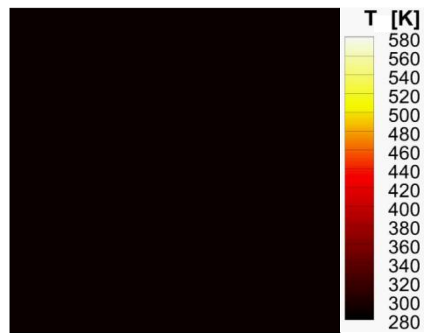
Experimental data / observations	Numerical simulation









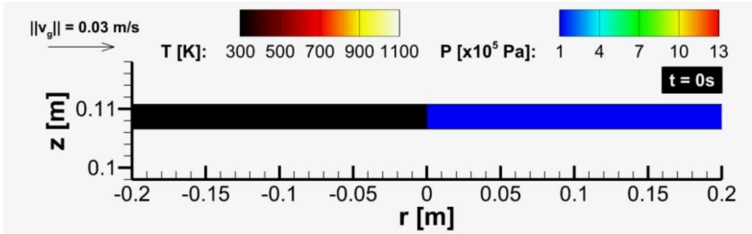


MoDeTheC + CEDRE

Pyrolysis / fire dynamics coupling

blade
fire
inject
modethec
adethec
ONERA CEDRE
ONERA ZEBULON

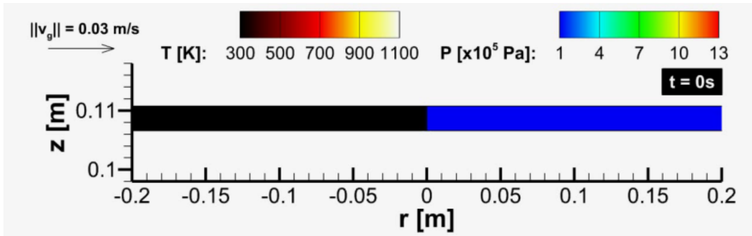
Defining relevant numerical coupling



Uncoupled simulation

$[\Phi]_{flame}(r,t) = [\Phi]_{flame}(r,t_0)$

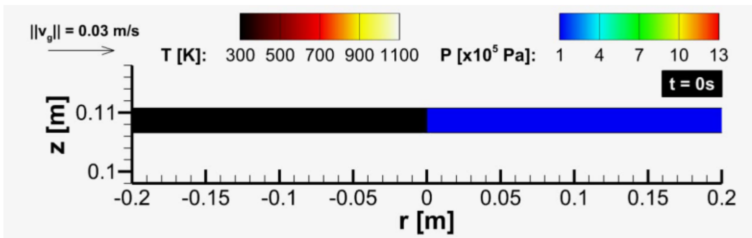
High heat flux causes important decomposition



Fluid/solid simulation

$[\Phi]_{flame} \Leftrightarrow [T]_{solid}$

(Convective) heat flux decreases as the surface temperature increases

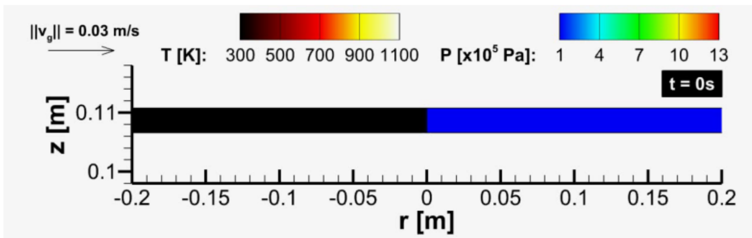


Inert gas blowing surface

$[\Phi]_{flame} \Leftrightarrow [T ; m_{N2}]_{solid}$

Film cooling effect

$[T_{gas}]_{solid} < [T_{gas}]_{fluid}$



Ignitable gas blowing surface

$[\Phi]_{flame} \Leftrightarrow [T ; m_{C3H8}]_{solid}$

Gas ignition extends the decomposition area

* Modélisation thermique de la dégradation d'un matériau composite soumis au feu
V. Biasi. **PhD thesis, University of Toulouse (2014)**

Conclusions

On-going and future work

- **Assessment of accurate material properties**
  - *Experimental methods relevant to the material scale (≫ REV)*
  - *Thermal properties at high temperature*
  - *Mechanical properties as a function of temperature (up to glass transition temperature)*
  - *Kinetics at high heating rates (Fast-TGA facility at ONERA)*
  - *Decomposition volatiles quantitative composition (combustion, toxicity, transport properties)*
  - *Homogenisation for relevant properties during decomposition*

- **Modelling**
  - *Ply-scale modelling to account for complex staking sequences*
  - *Delamination onset and growth*
  - *Composite and hybrid (composite/metal) junctions*
  - *Radiative heat transfer within semi-transparent heterogeneous materials*

- **Numerical simulation**
  - *Complex flames: gas and spray burners, pool fires, confined fires*
  - *Surface coupling to account for fire dynamics interaction with material off-gassing*
  - *Thermo-mechanical volume coupling to simulate heat and mass transfer within porous and cracked materials (post-delamination damage)*

ONERA

THE FRENCH AEROSPACE LAB