

ADVANCED MECHANICAL RESOLUTION IN CYRANO3 FUEL PERFORMANCE CODE USING MFRONT GENERATION TOOL

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CYRANO3 fuel performance code

MECHANICAL ANALYSIS

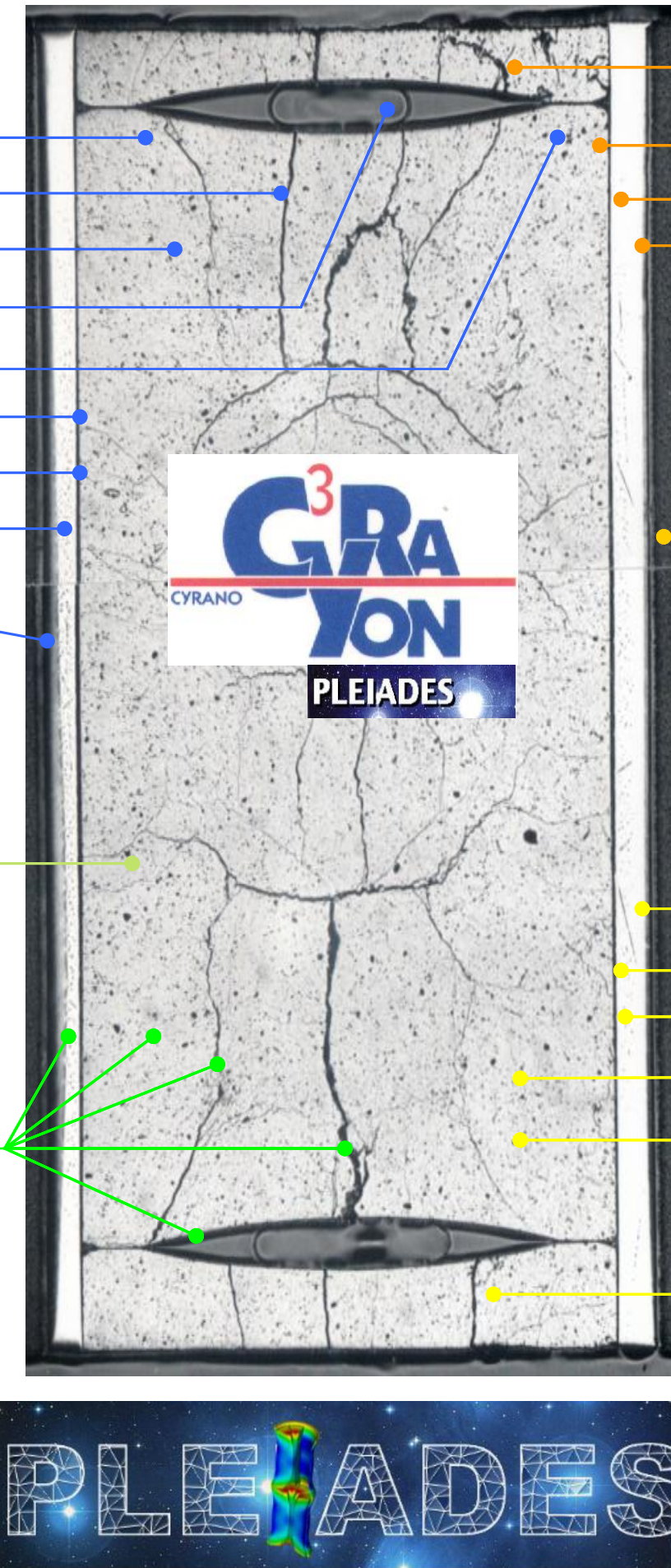
Fuel :
- poro-elasticity & visco-plasticity
- μ and macro cracking
- fragments relocation
- dishing
- hourglass
- hooking conditions (axial friction)
- PCI
- cladding : elasto-visco-plasticity
- external corrosion effect

NEUTRONIC

Radial power distribution
Fission products evaluation

INTERNAL PRESSURE

Free volume areas :
- Pellet-cladding gap
- plenum
- macro cracking
- open porosity
- chamfer
- dishing



THERMAL ANALYSIS

Radial temperature distribution
Gap conductivity
Cladding conductivity
Corroded alloy conductivity

THERMIC-HYDRAULIC

Heat transfert
Oxydation effects
Cooling's temperature

PHYSICAL-CHEMICAL

Corrosion
Hydruration
Irradiated cladding behavior
Pellet : irradiated local properties
- density, solid and fission gas swelling
- fission gas released
- thermal conductivity
- stoichiometry variation
- grain size

MFRONT code generator

MFRONT translates a set of physical equations into C++ instructions for local mechanical resolution :

- Various modelling hypotheses : tridimensional, plane strain, plane stress, etc.
- All kind of mechanical phenomena, such as plasticity, viscoplasticity and damage.
- Explicit (Runge-Kutta) and Implicit integration schemes

```
@ComputeStress { sig = D*eel;}  
@Integrator {real sigseq = sqrt(sigH*sig);  
n = H*sig/sigseq;  
feel --= deto - dp*n;  
dfeel_ddp = n;  
// Primay creep  
fp --= K1*dt*sigseq+K2*dt;  
dfp_ddeed = -theta*dt*K2*(n/D);
```

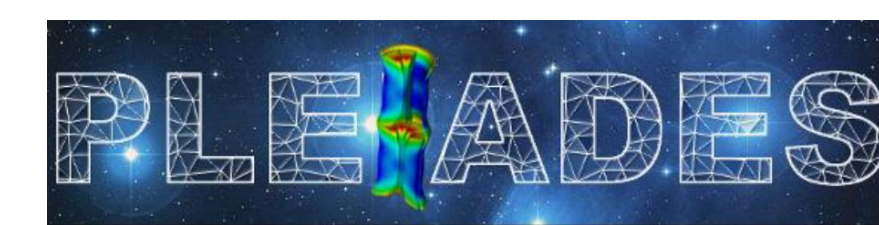
MFRONT instructions

MFRONT

Compilation

Libfile.so

Dynamic library that
can be linked to
different target
codes



A viscoplastic law implementation

Developed for Zirlo™ cladding material [9]

Valid for normal and incidental conditions

Constitutive equations :

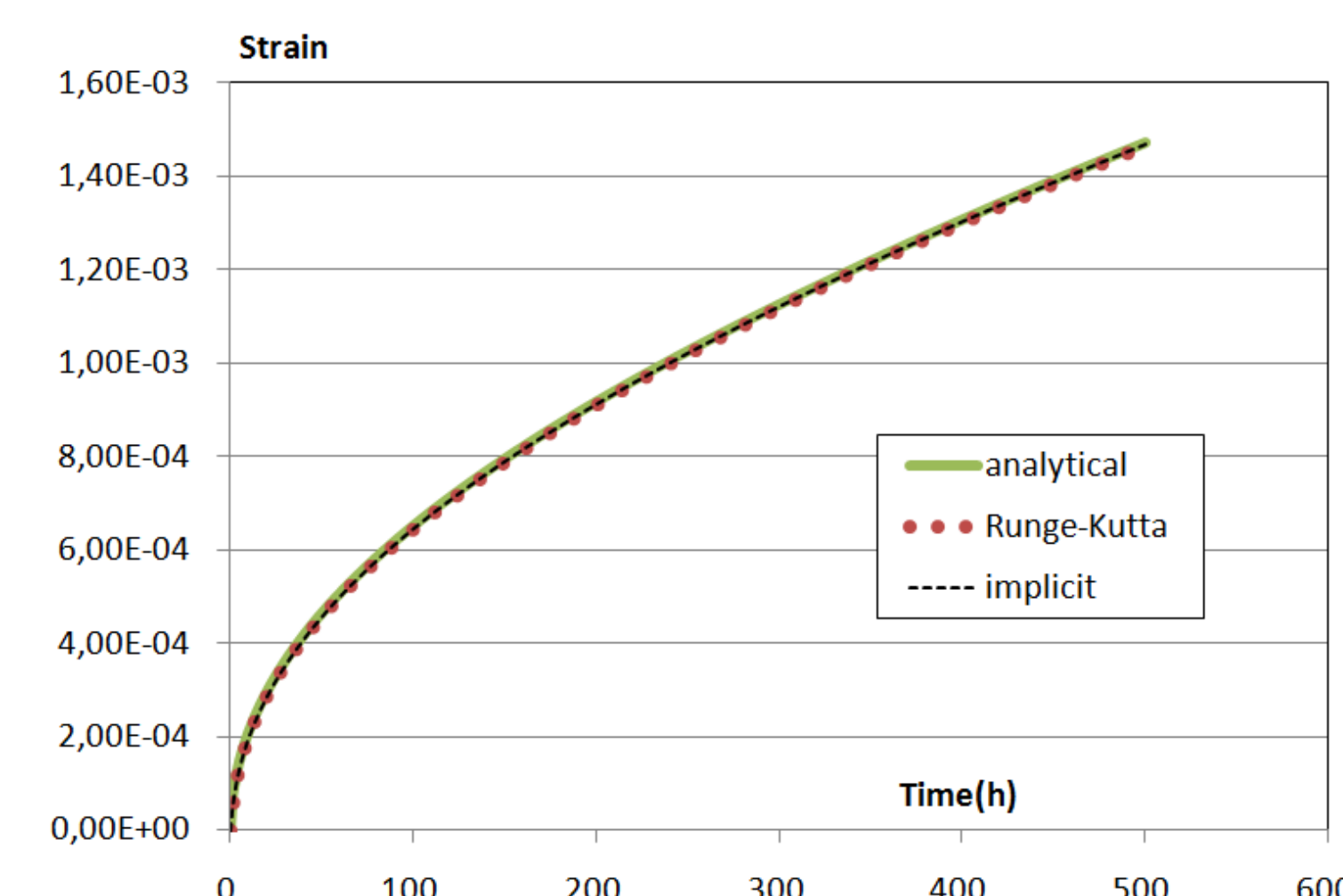
$$\varepsilon_{an}^{eq} = \frac{2}{\sqrt{3}} \left[\varepsilon_{sp} \left(1 - e^{-C\sqrt{\varepsilon_s t}} \right) + \varepsilon_s t \right]$$

$$\varepsilon_{sp} = B \varepsilon_s^b * [2 - \tanh(D \varepsilon_s)]^d$$

$$\varepsilon_s = \frac{AE}{T} e^{-\frac{Q}{RT}} \left[\sinh \left(\frac{2}{\sqrt{3}} a_{irr} \frac{\sigma_{eq}}{E} \right) \right]^n + C_0 \phi^{c_1} \left(\frac{2}{\sqrt{3}} \sigma_{eq} \right)^{c_2}$$

$$a_{irr} = a [1 - A_1 \exp(-A_2 \phi^{A_3})]$$

Isotropic Von Mises behaviour
Primary and secondary creep terms
Irradiation and thermal creep
Effect of fast neutron flux Φ
Effect of fast neutron fluence ϕ
Effect of temperature T



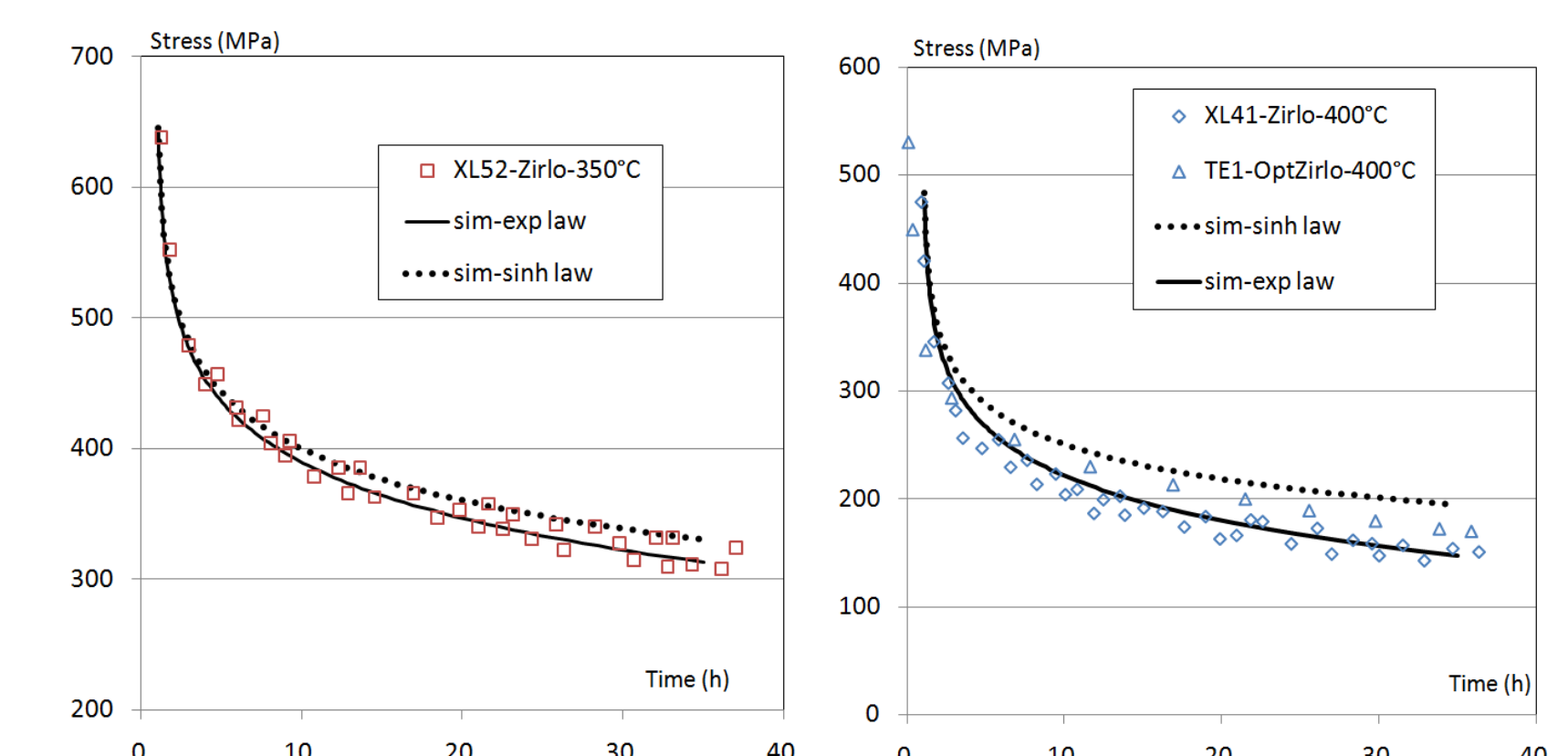
Comparison between an analytical solution and MFRONT explicit and implicit implementations

Comparison with a reference solution

- stress-relaxation tests (irradiated) [9]
- simulation of MFRONT implemented law thanks to MTEST software
- comparison with the exponential approximation from [9]

Verification of MFRONT implementation

- implicit and explicit schemes
- comparison with time-explicit creep response of the constitutive law
- simulation of MFRONT implemented law thanks to MTEST software



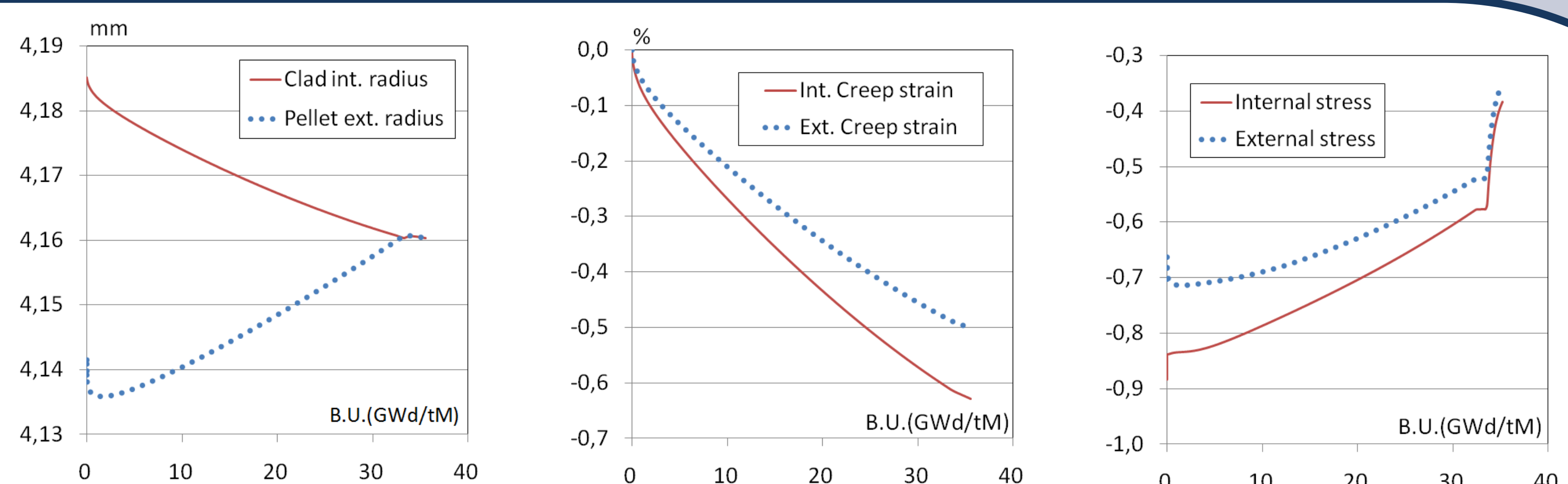
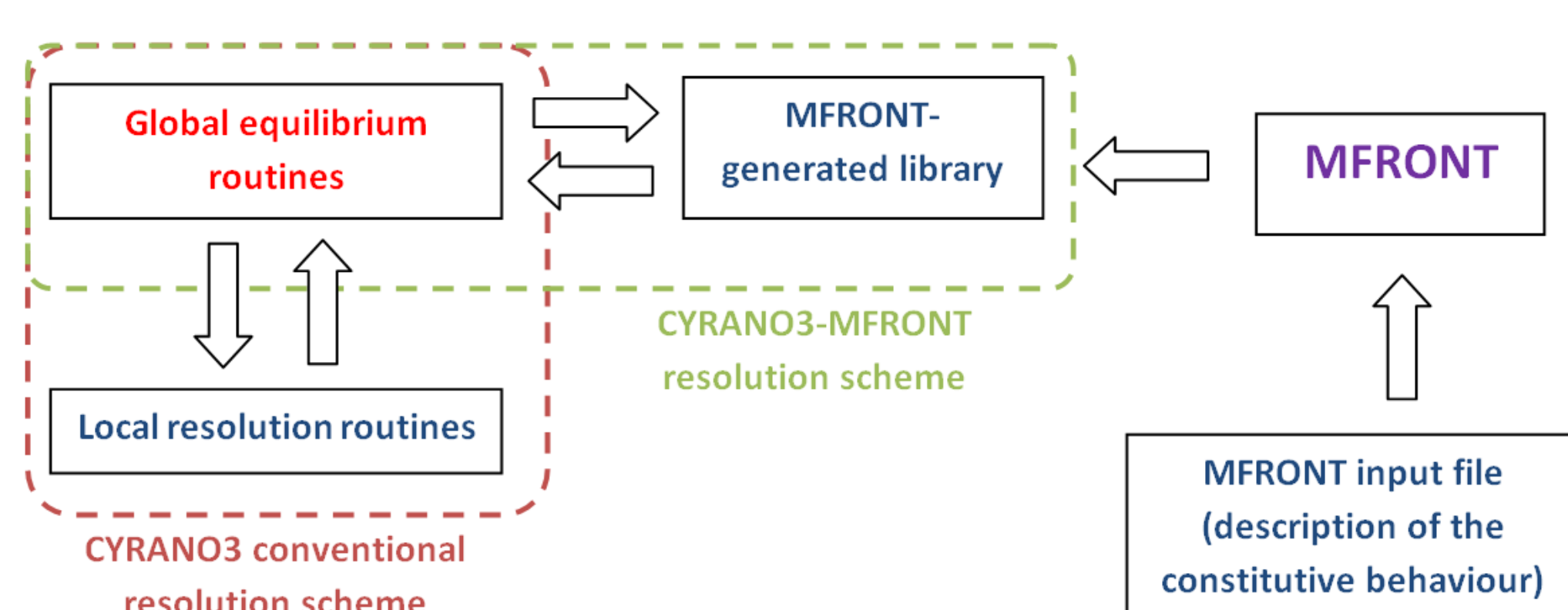
Comparisons between experimental results from [9] and simulations using different approximations of the creep law

CYRANO3 computation

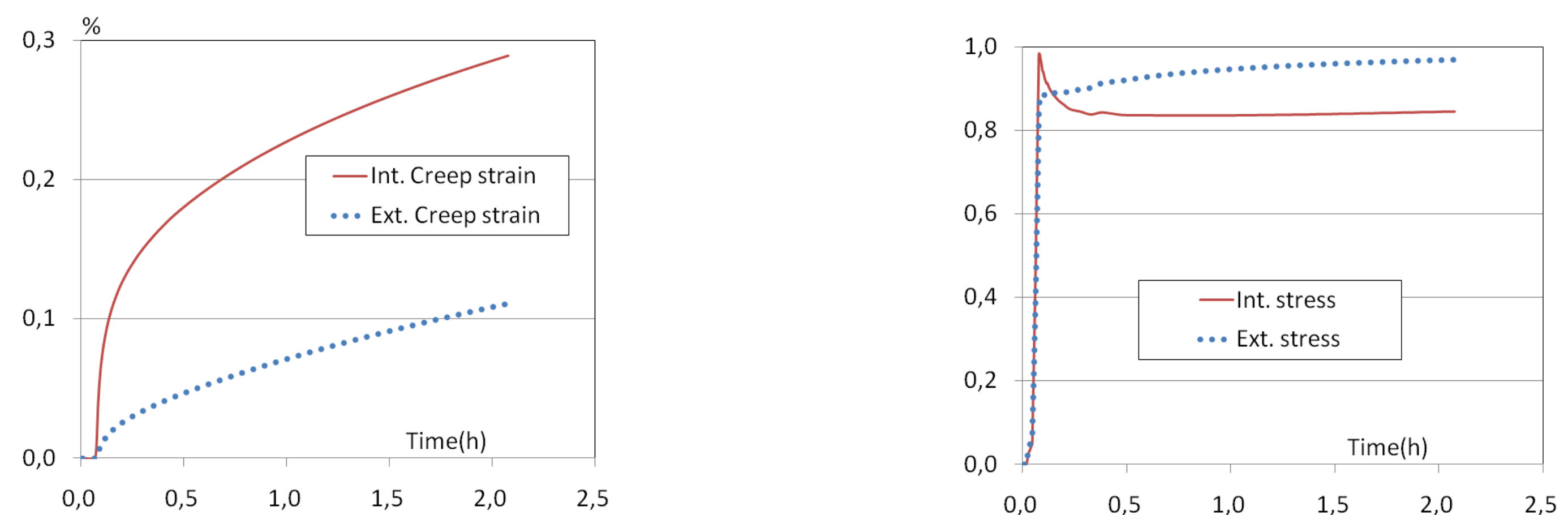
CYRANO3 case study

- irradiation of a typical PWR UO₂/Zirlo™ rod at 180W/cm up to 35GWd/tM (step 1);
- 100W/cm/min power ramp up to 350W/cm + 2 hours holding time (step 2).

Typical PWR severe incidental conditions...



Results of step 1 computation – evolutions as a function of rod burn-up left : pellet and cladding radii center : cladding inner and outer creep strain right : cladding inner and outer normalised hoop stresses



Results of step 2 computation – left : cladding inner and outer creep strain right : cladding inner and outer normalised hoop stresses