PLATFORM DEMONSTRATION : RPV EMBRITTLEMENT COMPUTING A DUCTILE-BRITTLE TRANSITION TEMPERATURE T_0 USING LOCAL APPROACH TO FRACTURE

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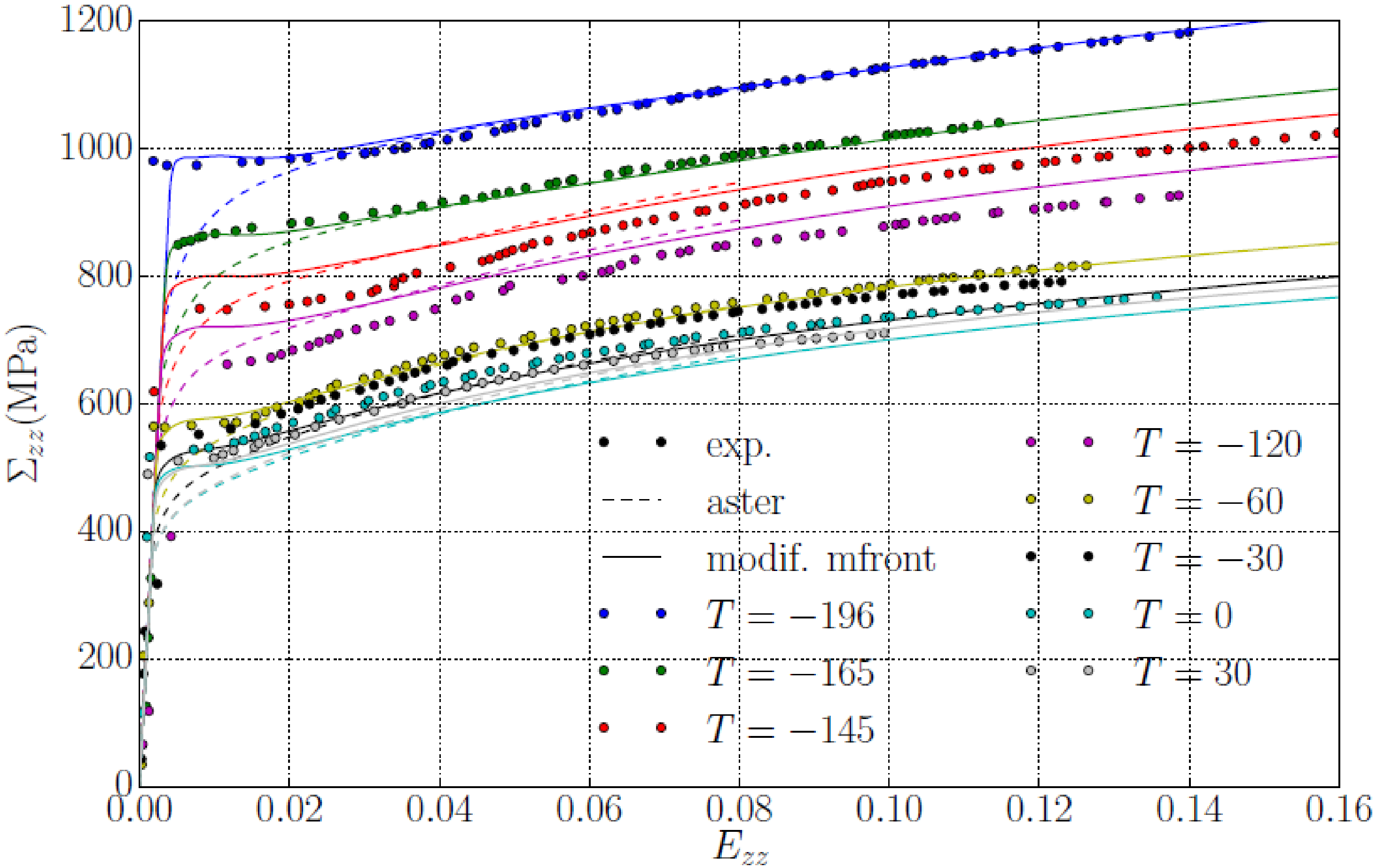
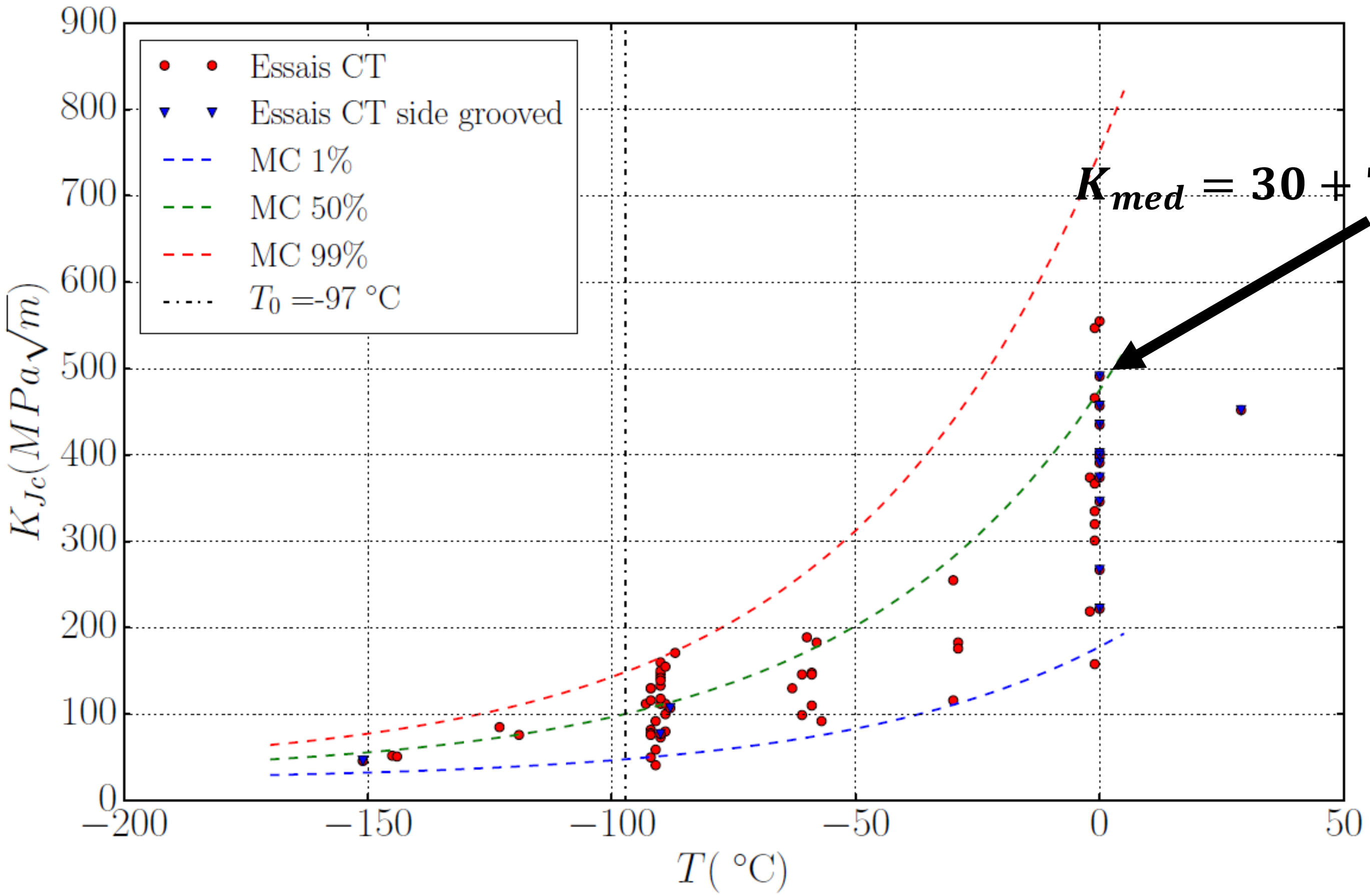
H1BQ12 Steel tensile properties

- Pressure vessel steel
- Behaviour has been characterised for a wide range of temperatures
- Unirradiated condition



H1BQ12 Steel fracture properties



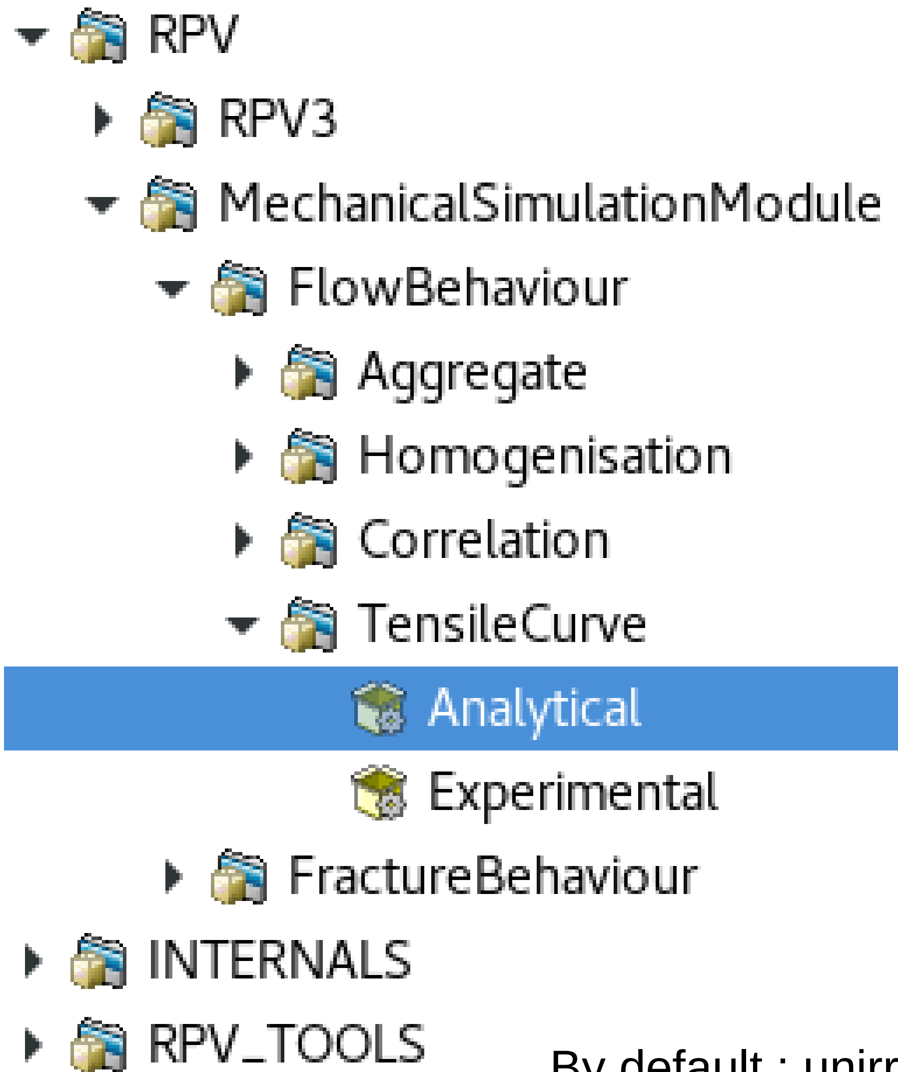
$$K_{med} = 30 + 70\exp(0.019(T - T_0))$$

$$P_f(K_{Jc} \le K) = 1 - \exp\left[-\frac{B}{B_0}\left(\frac{K - K_{min}}{K_{med} - K_{min}}\right)^4\right]$$

Master Curve

- Initial reference temperature : -97°C
- Toughness is about 100 MPa.m$^{-1/2}$
- Well identified plasticity and local approach to failure models are relevant

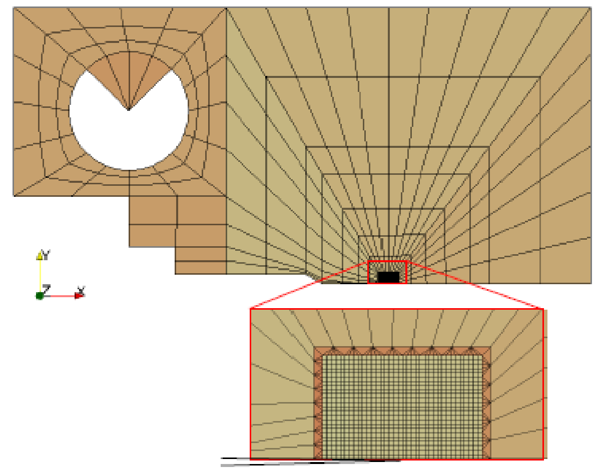
Toughness prediction : tensile curve



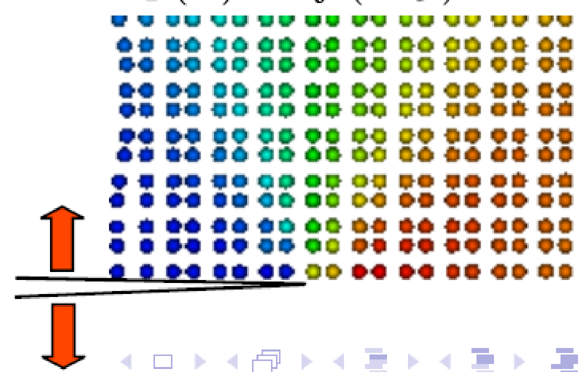
By default : unirradiated H1BQ12 steel

CT Calculation with the platform

- To circumvent the limitations of the Master Curve approach, the local approach to failure proposes a chaining of a plastic calculation and a failure post-treatment
- The plastic calculation proposed in the platform is available in the RPV Toughness Module as "CTCalculation"
- It is a 2D calculation using Code_Aster as solver
- possible chainings with homogenized crystal plasticity law to benefit from lower scale plastic models



$$\sigma_I(x) = f(K_J)$$

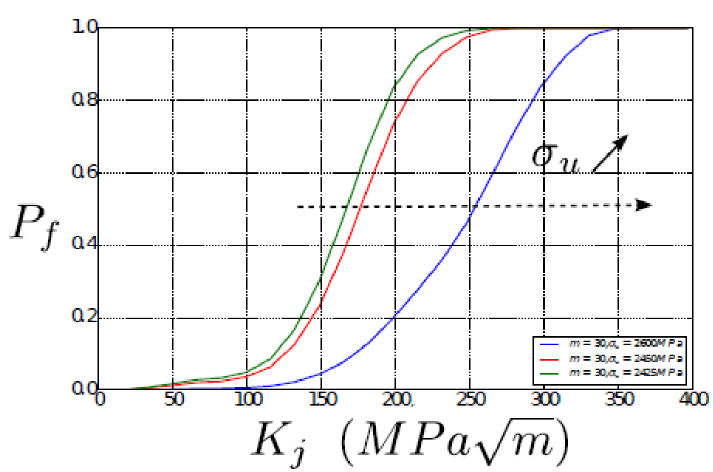


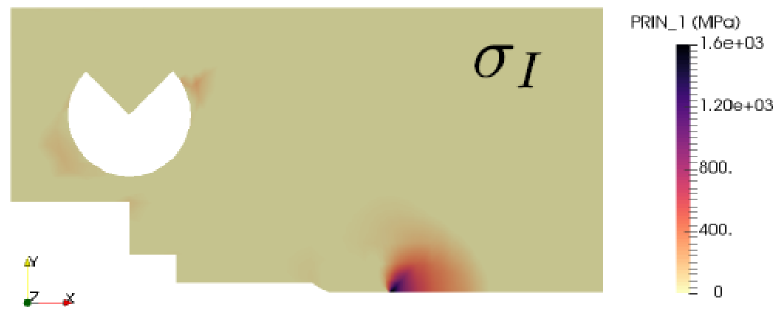
Beremin model

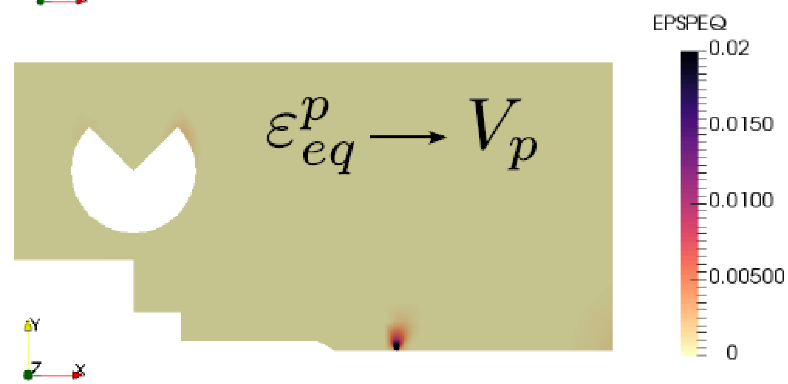
- $\forall K_j(t_i)$
  - fitting a Weibull stress σ_W on the plastic Volume V_p using the σ_I field
  - Compute the failure probability P_f

$$\sigma_W = \left(\int_{V_p} {\sigma_I}^m \frac{dV}{V_0} \right)^{m^{-1}}$$

$$P_f = 1 - \exp\left[- \left(\frac{\sigma_W}{\sigma_u} \right)^m \right]$$



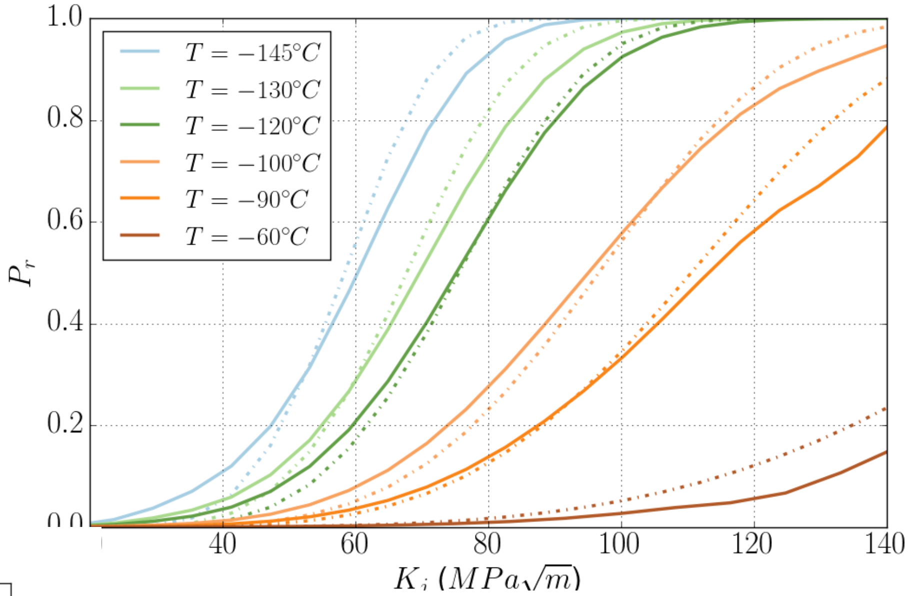


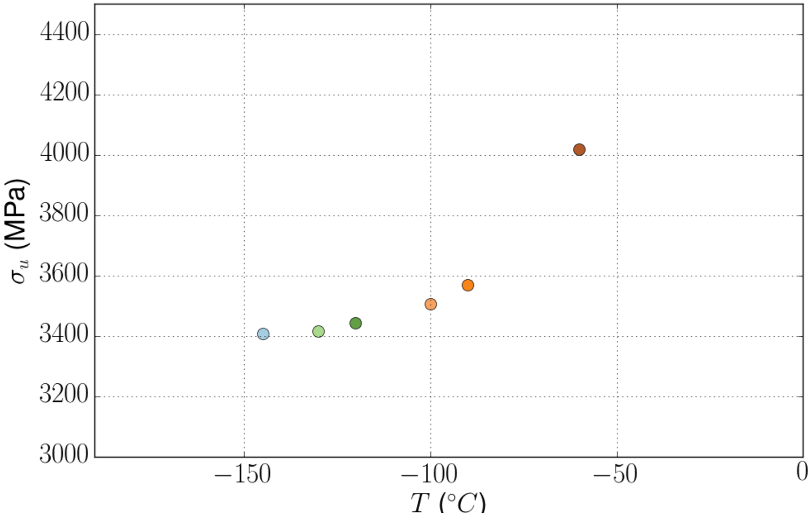


- Beremin parameters : m, σ_u, V_0

Correlation Beremin – Master Curve

Solid Line = Beremin
Dashed Line = Experimental Master Curve



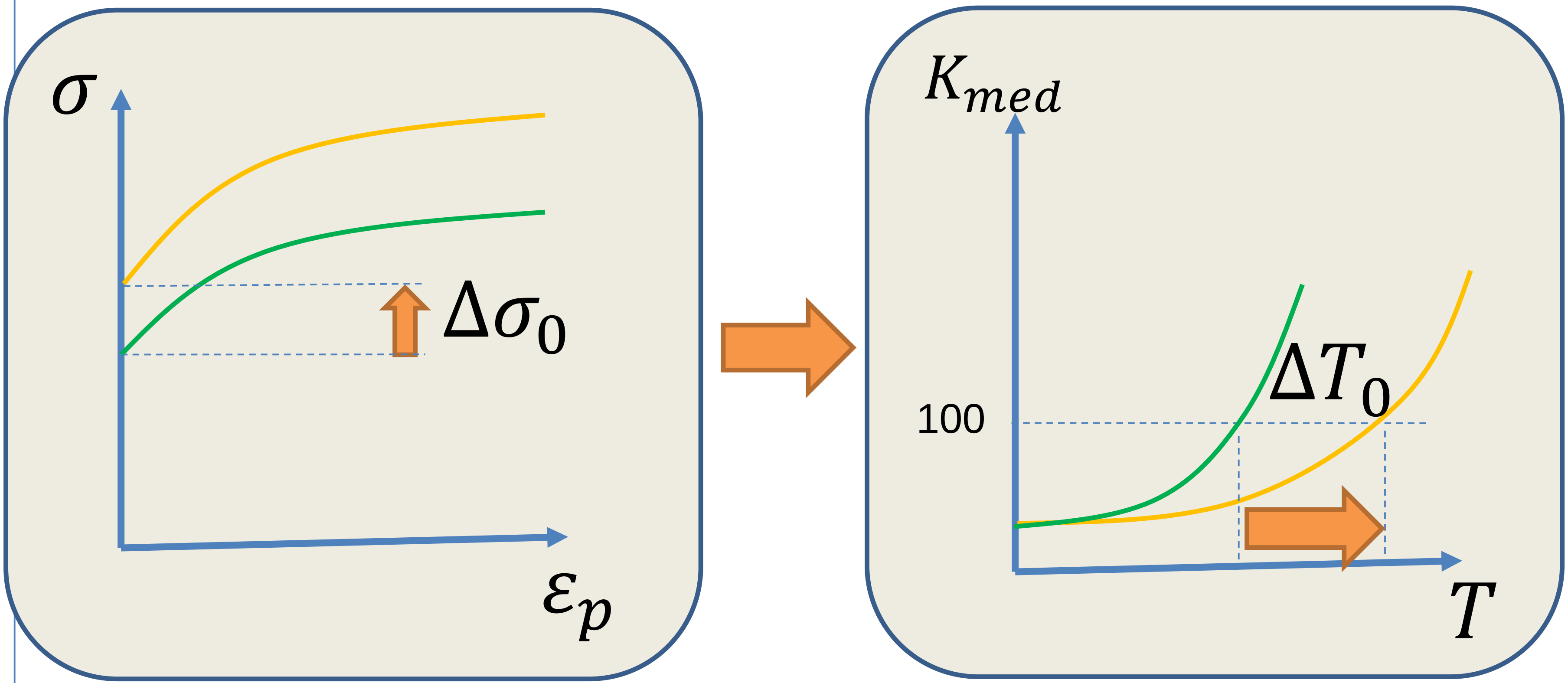


$$\sigma_u = A + B\ exp(C\ T)$$

P. Forget (EMMC9)

A (MPa)	B (MPa)	C
3267	961	0.025

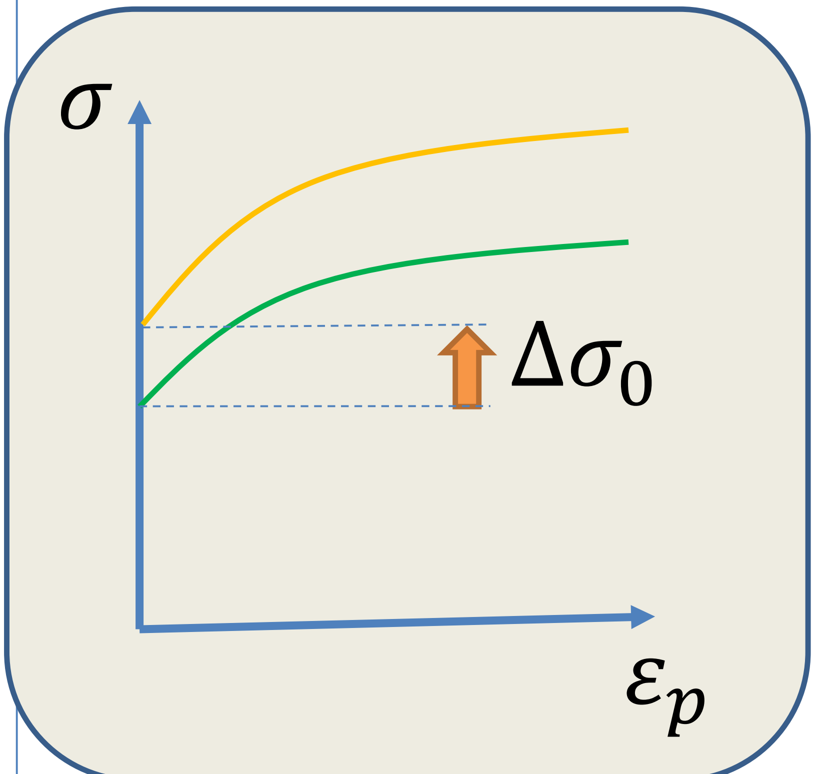
Irradiation effects on plasticity

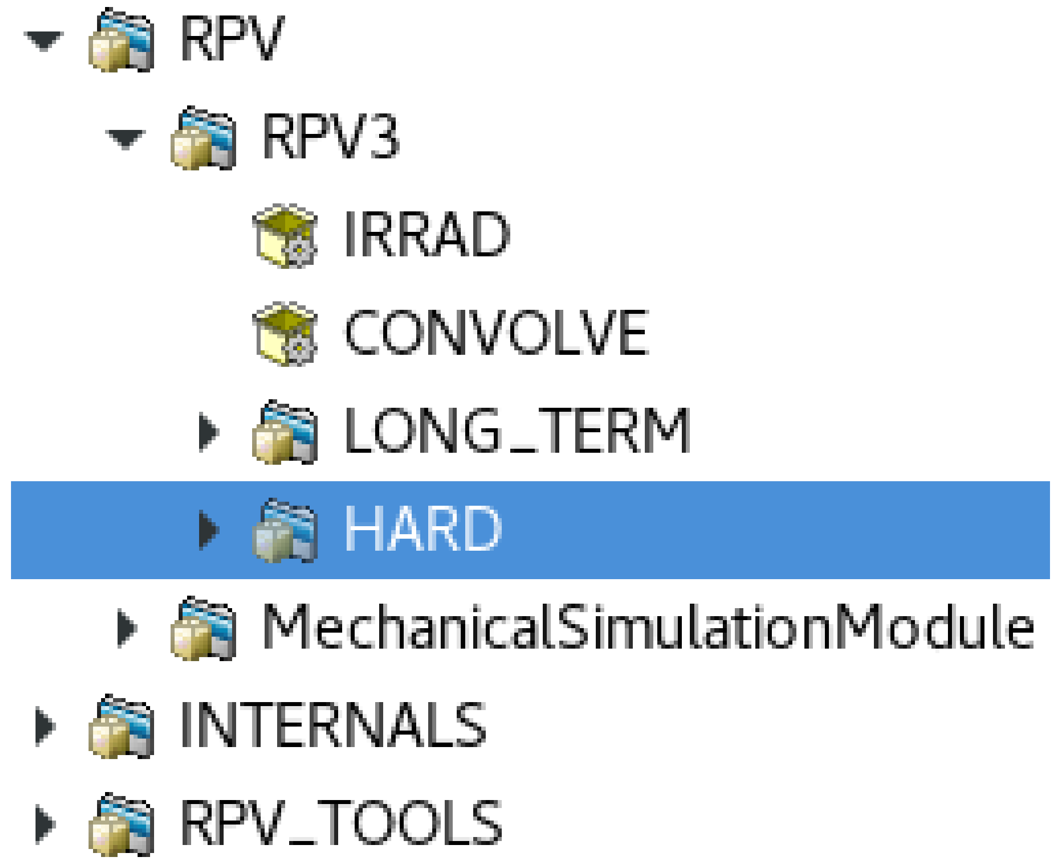


Irradiation effects on the tensile behavior : irradiation hardening

- Increase of yield stress
- Limited hardening modulus increase

Irradiation effects on plasticity

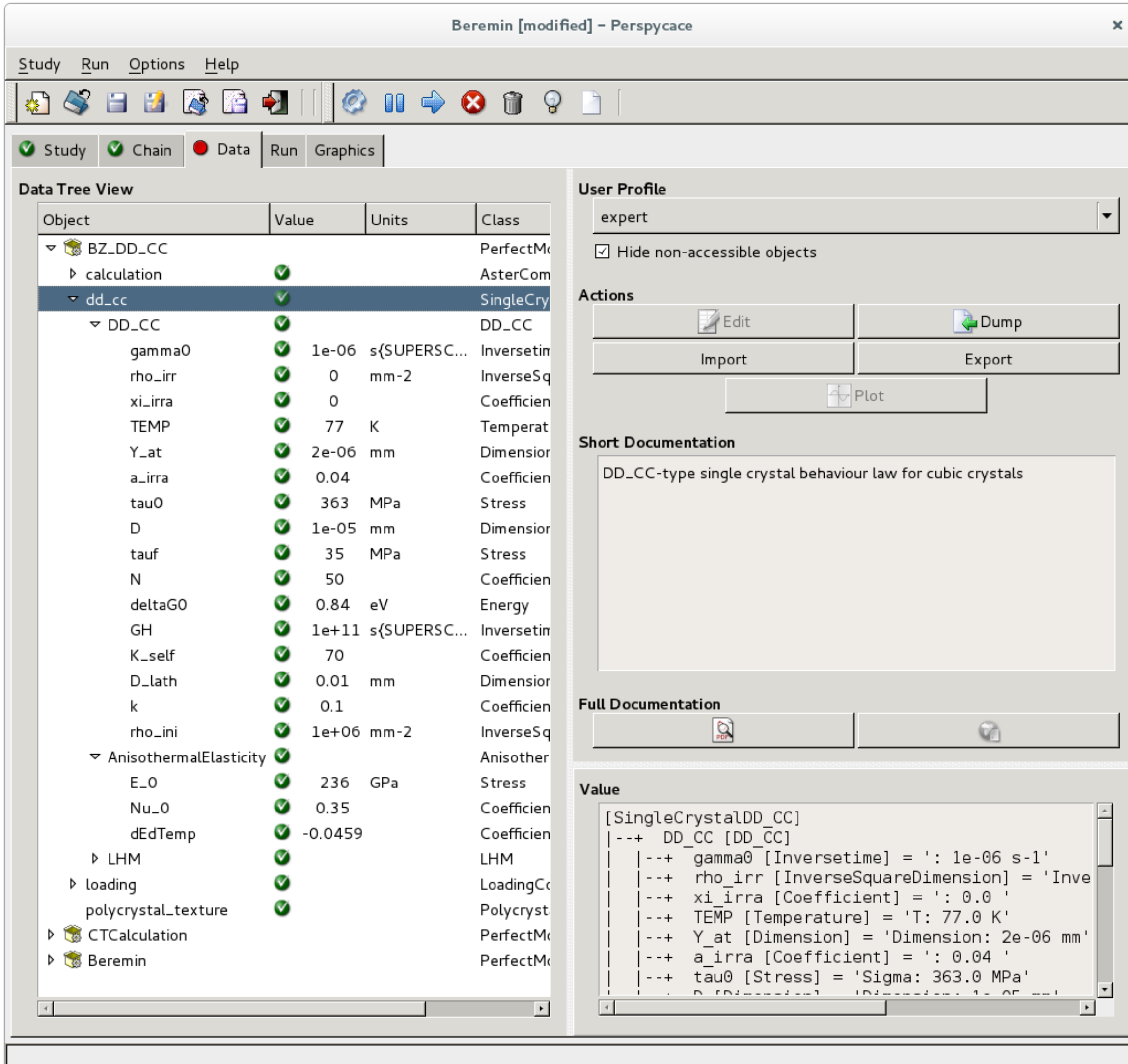




Yield stress increase :
Computed by using the Taylor coefficient

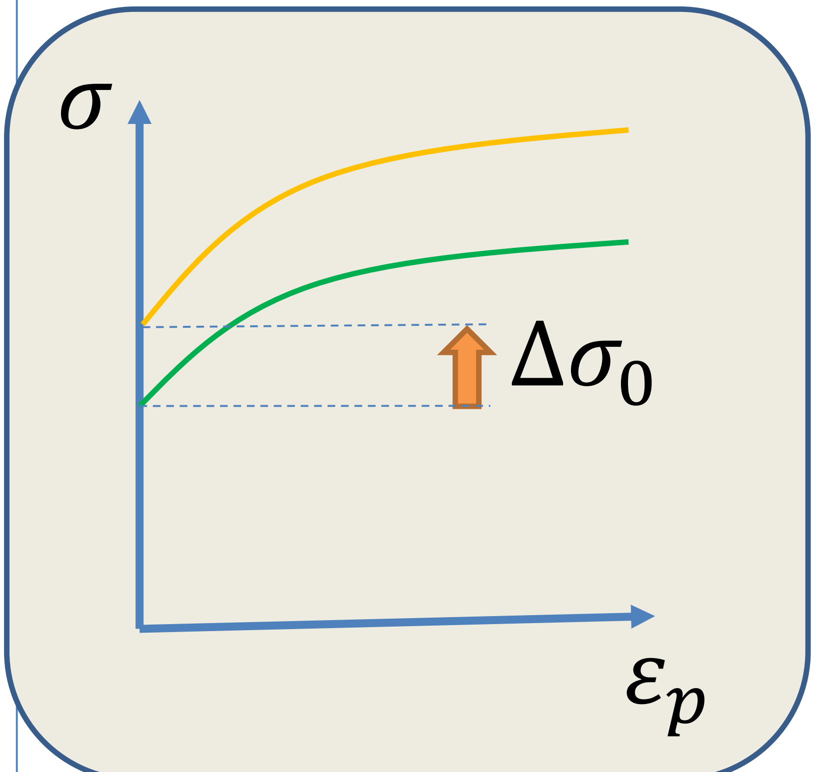
$$\Delta\sigma_0 = 2{,}5\ \Delta CRSS$$

Irradiation effects on plasticity



Irradiation and metallurgical features of the steel need to be known

Irradiation effects on plasticity



Analytical			PerfectMod...	user
DeltaSigmaY	0	MPa	Stress	user
Yield_stress			Analytical_yi...	user
n	1.2		Coefficient	user
A_Rp02	430	MPa	Stress	user
temperature	-120	°C	Temperature	user

Irradiation effect on fracture

Cleavage stress equation :

$\sigma_u = A + B\ exp(C\ (T - \Delta T_u)),$

B.Tanguy, A. Parrot (ASME 2011)

$\Delta T_u = \ \Delta T_0,$

For the different irradiations :

$\Delta T_0 = \alpha \Delta \sigma_0, \quad with \quad \alpha = 0.7$

Sokolov relation

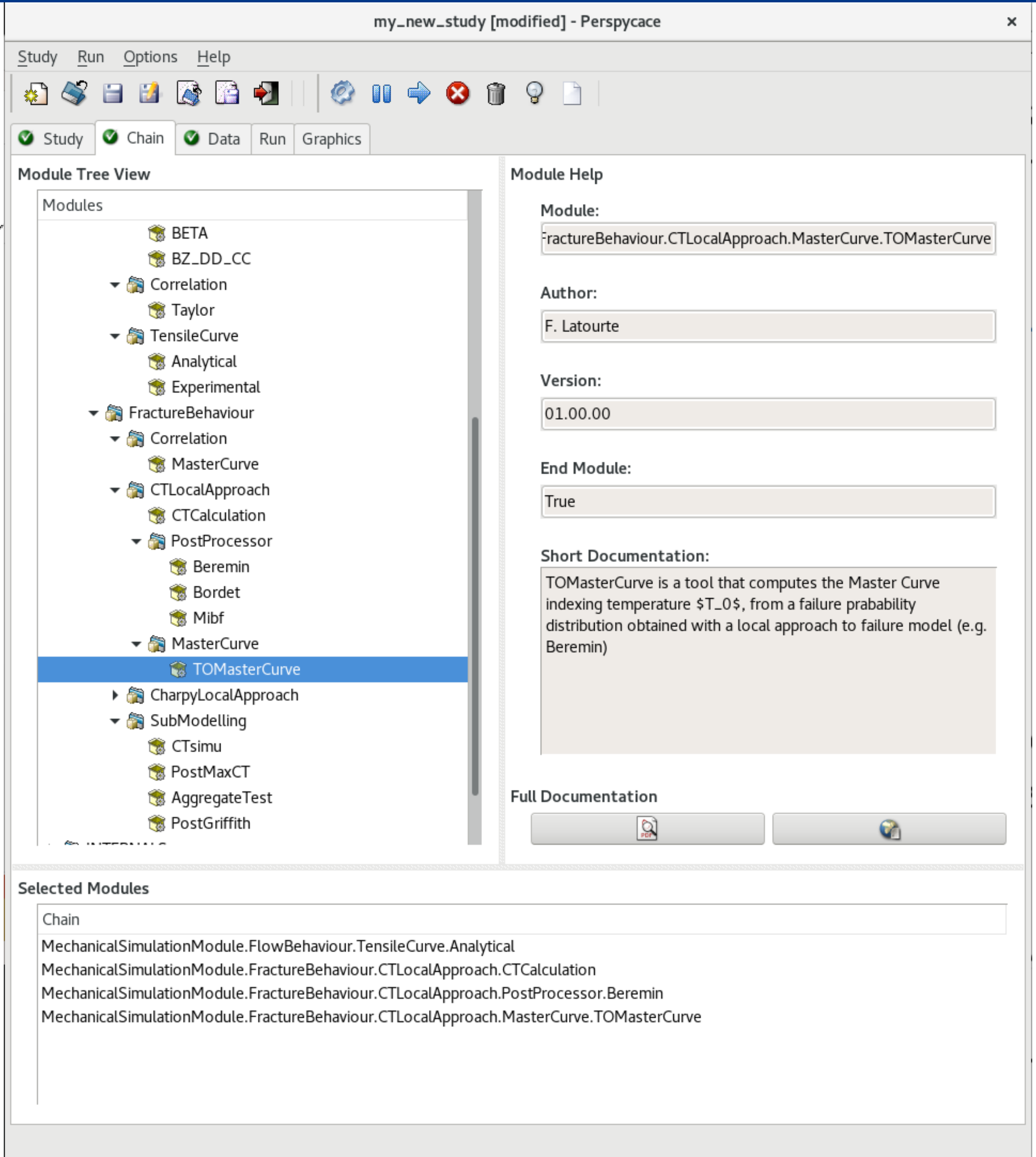
Used to set the Beremin parameters

- **Temperatures**
- **Irradiation conditions**

$\Delta\sigma_0$, MPa	T, °C	σ_u, MPa
0	-120	3314
50	-120	3286
50	-90	3309
50	-60	3356
100	-90	3284
100	-60	3304
100	20	3542
150	-60	3282
150	20	3381

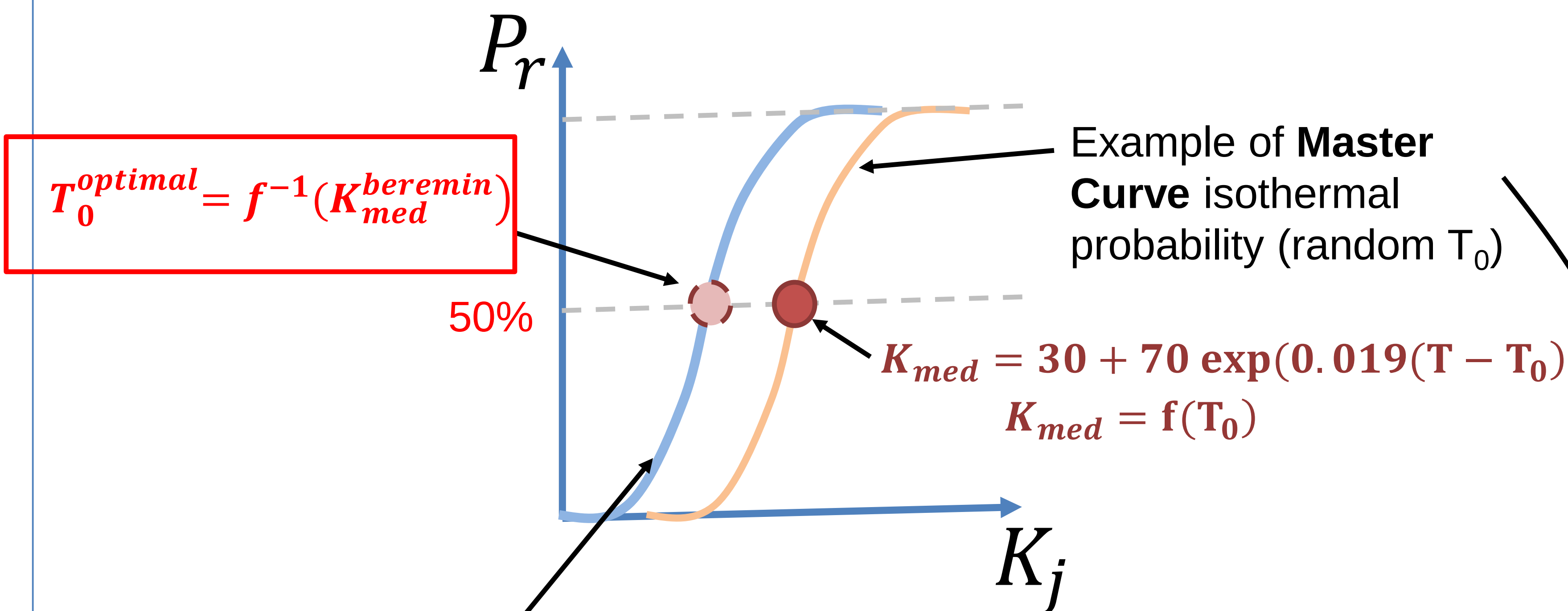
Modules chaining

list of available modules



chain

Fitting T_0 with TOMasterCurve



Output of the platform : Beremin failure probability

Toughness value corresponding to the median probability is computed

T0MasterCurve submodule

- Inverts the equation $K_{med} = f(T_0)$
- Obtain the transition temperature

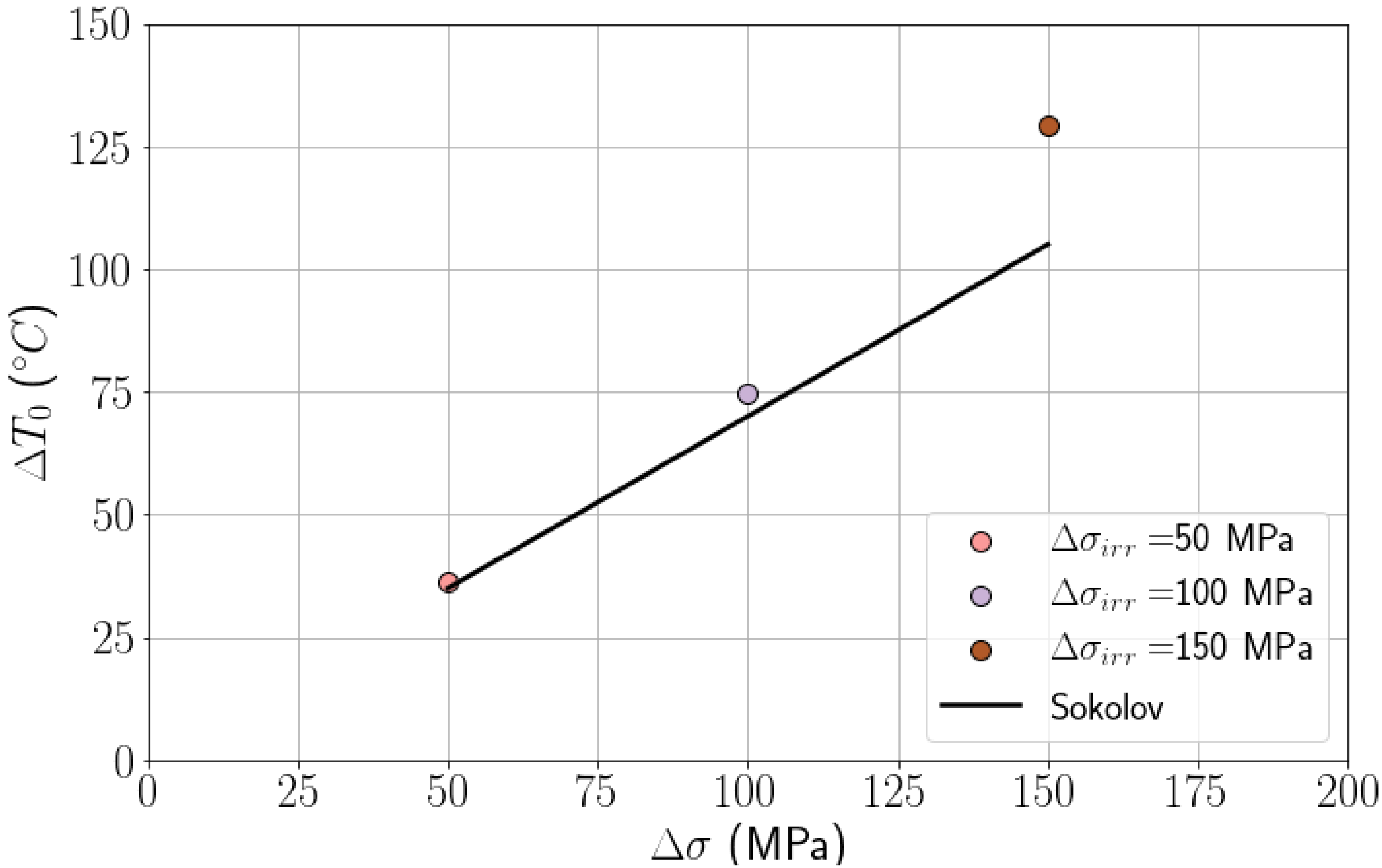
$$P_f(K_{Jc} \leq K) = 1 - \exp\left[-\frac{B}{B_0}\left(\frac{K - K_{min}}{K_{med} - K_{min}}\right)^4\right]$$

Evolution of T_0 with irradiation Different yield stress increases

Calc. number	$\Delta\sigma_0$, MPa	T, °C	T_0, °C
0	0	-120	-102
1	50	-120	-80
2	50	-90	-74
3	50	-60	-62
4	100	-90	-53
5	100	-60	-41
6	100	20	-6
7	150	-60	-20
8	150	20	24

At different temperatures we obtain different values of T_0
Find the best T_0 value for each irradiation hardening
- Linear interpolation at $100\ MPa\sqrt{m}$

Local Approach
Calculations and identifications



Technical work achieved

- Computing a ductile-brittle transition temperature T_0
  - Beremin model
- Computing failure curve
  - MIBF model

The SOTERIA Consortium

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SOTERIA Website – coming soon

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The Micro-structurally Informed Brittle Fracture (MIBF) model

- Including local stress distribution : effect of a variable stress field resulting from the bainitic microstructure of the RPV steel ahead of the crack.
- INPUTS : irradiation-induced hardening level, particle size distribution, surface energy, grain-size, grain orientation, grain-scale stress fields (a distribution of principal stresses)
- RPV steel microstructure ⇒ local stress distribution σ^* inside V_0 are captured from crystal plasticity modelling.

- Ref. : J. Nucl. Mat. 406 (2010) 91-96

MIBF model

- There is a general formulation that most Local Approach models share to describe the local probability of failure (for a point, i):

$$p_{f,i} = \int_{r_{c,i}}^{\infty} p_{c,i} f(r) dr$$

- r is the particle radius, $r_{c,i}$ is the critical micro-crack for propagation, $p_{c,i}$ is the probability of micro-crack nucleation and f(r) is the probability density of the initiators size.

MIBF model

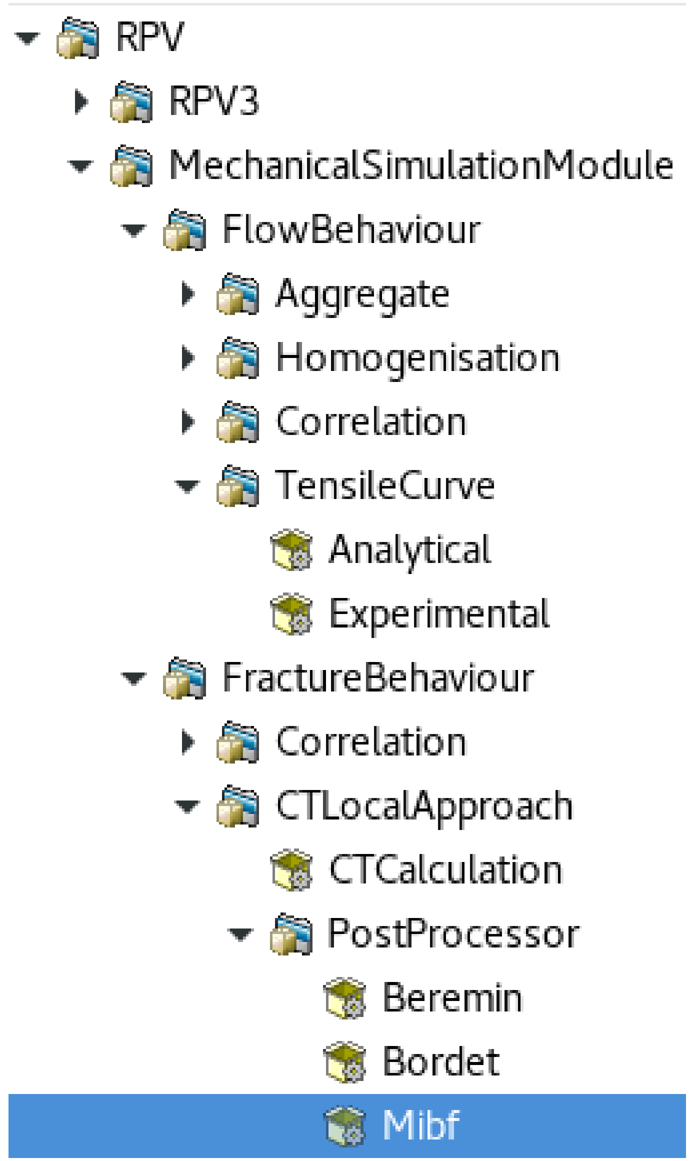
- The basic approach in the MIBF model is then similar to the Beremin model (nucleation based on plasticity and propagation based on the Griffith term).

$$\sigma_c = \sqrt{\frac{\pi}{2(1-\nu^2)} \cdot \frac{E \cdot \gamma_f}{r}}$$

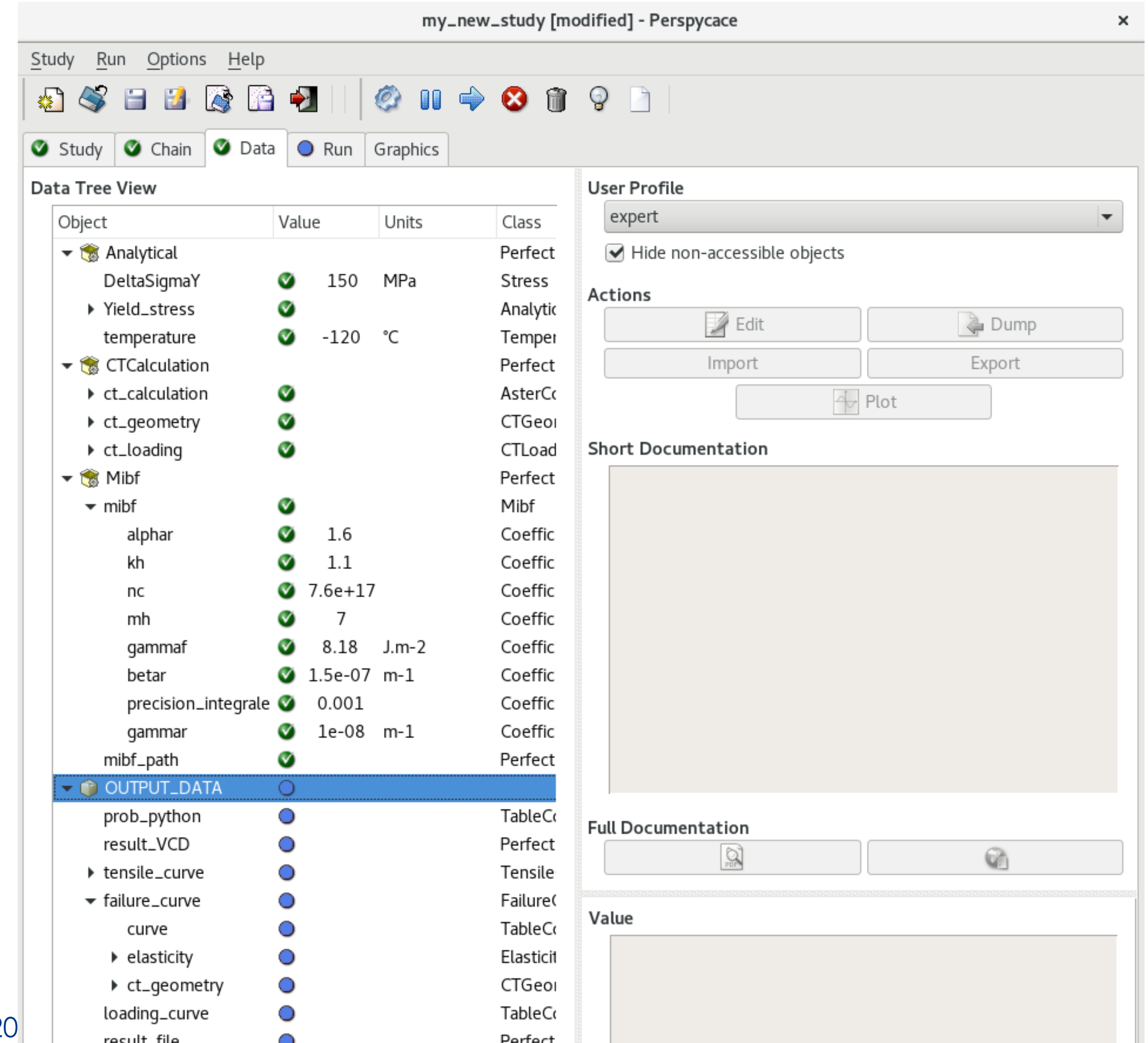
- The implementation allows a range of f(r) laws to be used.

$$P_f(V_p, \Sigma) = 1 - \exp\left(\int_{V_p} \ln\left(1 - P_f(V_0, \sigma)\right) \frac{dV}{V_0} \right)$$

MIBF model


RPV
RPV3
MechanicalSimulationModule
FlowBehaviour
Aggregate
Homogenisation
Correlation
TensileCurve
Analytical
Experimental
FractureBehaviour
Correlation
CTLocalApproach
CTCalculation
PostProcessor
Beremin
Bordet
Mibf

MIBF model


my_new_study [modified] - Perspycace
Study Run Options Help
Study Chain Data Run Graphics
Data Tree View
Object Value Units Class
Analytical Perfect
DeltaSigmaY 150 MPa Stress
Yield_stress Analytic
temperature -120 °C Temper
CTCalculation Perfect
ct_calculation AsterC
ct_geometry CTGeo
ct_loading CTLoad
Mibf Perfect
mibf Mibf
alphar 1.6 Coeffic
kh 1.1 Coeffic
nc 7.6e+17 Coeffic
mh 7 Coeffic
gammaf 8.18 J.m-2 Coeffic
betar 1.5e-07 m-1 Coeffic
precision_integrale 0.001 Coeffic
gammar 1e-08 m-1 Coeffic
mibf_path Perfect
OUTPUT_DATA
prob_python TableC
result_VCD Perfect
tensile_curve Tensile
failure_curve Failure
curve TableC
elasticity Elasticit
ct_geometry CTGeo
loading_curve TableC
result_file Perfect
User Profile
expert
Hide non-accessible objects
Actions
Edit
Dump
Import
Export
Plot
Short Documentation
Full Documentation
Value

MIBF model

Analytical				PerfectMod...	user
DeltaSigmaY	✓	0	MPa	Stress	user
Yield_stress	✓			Analytical_yi...	user
temperature	✓	-120	°C	Temperature	user
CTCalculation				PerfectMod...	user
ct_calculation	✓			AsterCompu...	user
ct_geometry	✓			CTGeometry	user
ct_loading	✓			CTLoadingC...	user
Load_rate	✓	1481	N/s	Coefficient	user
Load_max	✓	7.404e+04	N	Force	user
Steps	✓	25	steps	Integer	expert
Mibf				PerfectMod...	user
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result_VCD	●			PerfectFile	user
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failure_curve	●			FailureCurve	user
curve	○			TableCoeffic...	user
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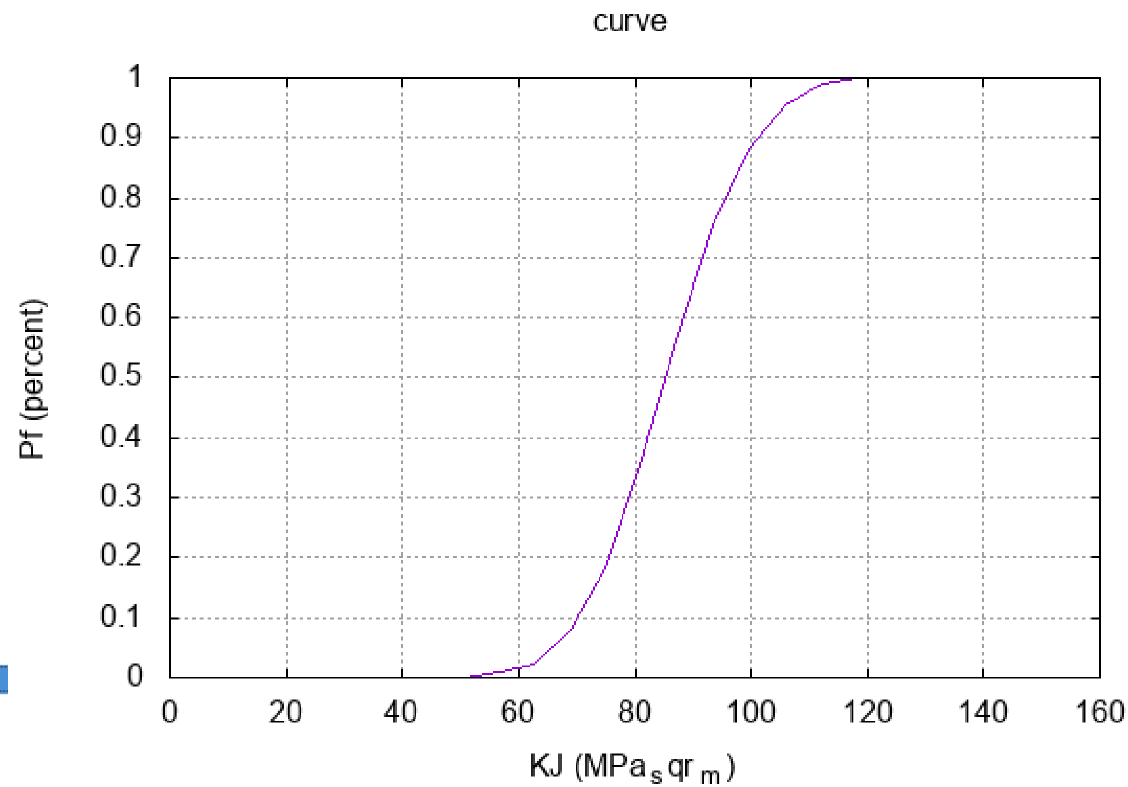
result_file	●			PerfectFile	user

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1.999756921 0.0136087714322 2961.63999231 0.0 4.2833268285
3.999513842 0.027220302127 5923.27999997 0.0 9.49570126188
5.999270763 0.040849732221 8884.92000002 0.0 15.243061574
7.999027684 0.0545127915357 11846.56 0.0 21.0983319219
9.998784605 0.0682174961607 14808.2 0.0 26.9965369651
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Technical work achieved

- Computing a ductile-brittle transition temperature T0
  - Beremin model
- Computing failure curve
  - MIBF model

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