THERMEC'2025
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Processing, Fabrication, Properties, Applications
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LIÈGE université Sciences Appliquées

Materials and Solid Mechanics

DREVER International

Session H7 – Modeling & simulation

Application of Activation-Function Norton law (AFN) to predict the two-step minima creep deformation observed in Incoloy 800H

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07 – July – 2025

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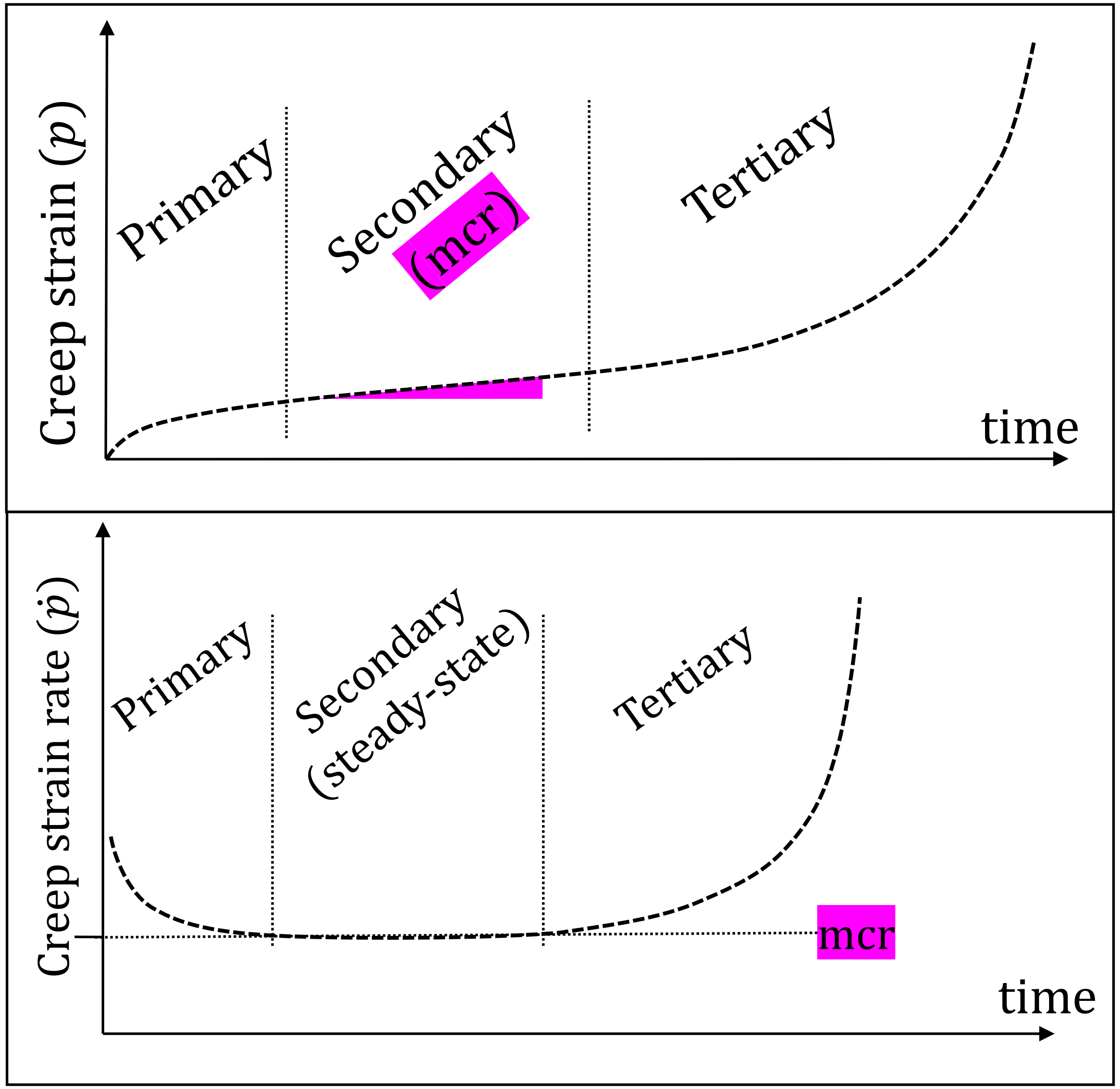
- 4000-8987
- 4002-1907

Outlines

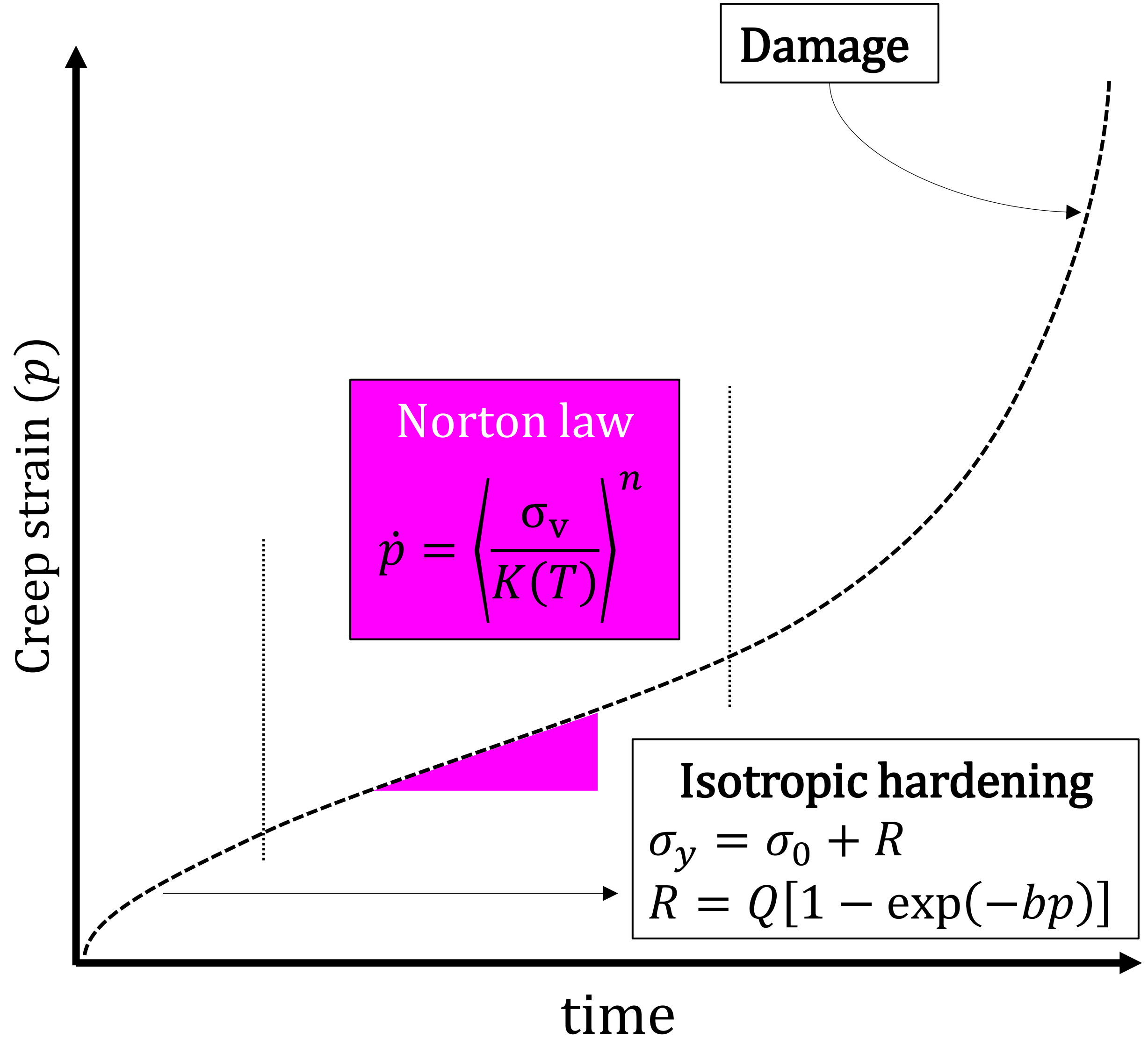
1. Introduction
2. Modeling of non-classical creep response
3. Model validation: creep & damage prediction
4. Conclusions & prospects

Classical creep

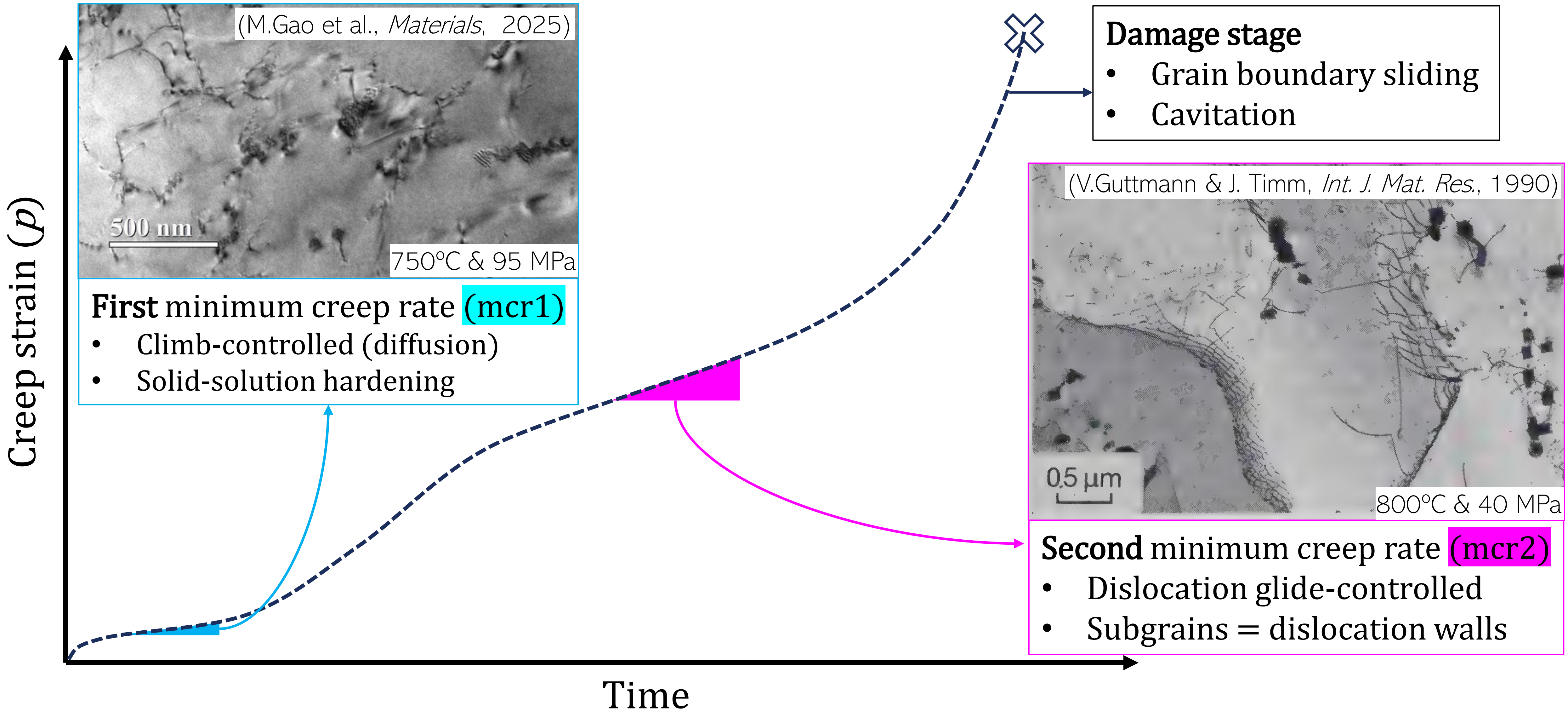
classical creep response



conventional creep modeling

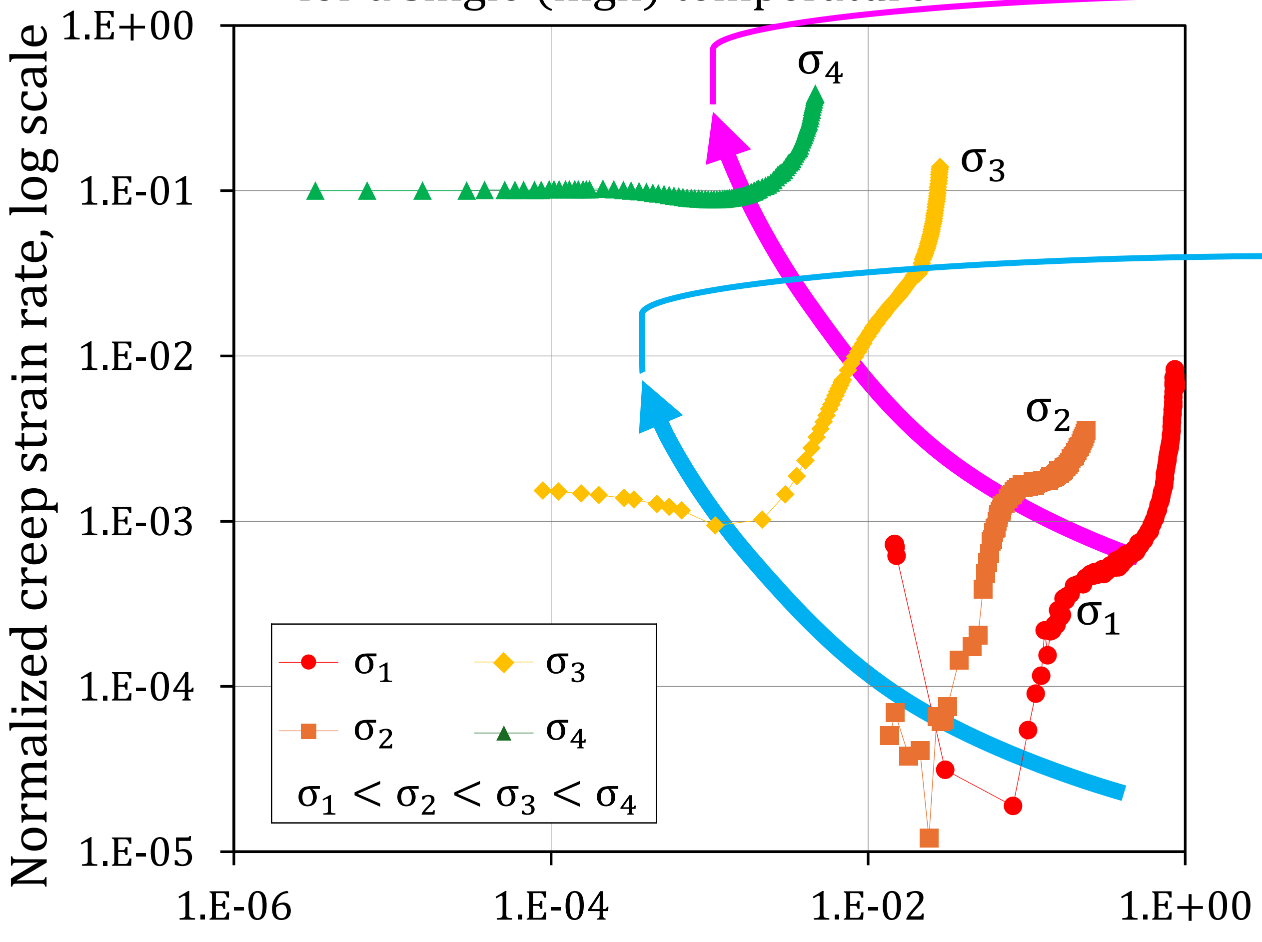


Physics of non-classical creep of 800H alloy



ULiège experimental observations

Superposition of creep curves of 800H
for a single (high) temperature



mcr2: steady-state creep rate

- Predictable with conventional Norton law

$\rightarrow \dot{p} = f(\sigma, T)$

mcr1: observed if

- High temperature + low stress[4]
- As-received condition (not aged)[5]

$\rightarrow \dot{p} = f(\sigma, T)$

∴ Challenge:

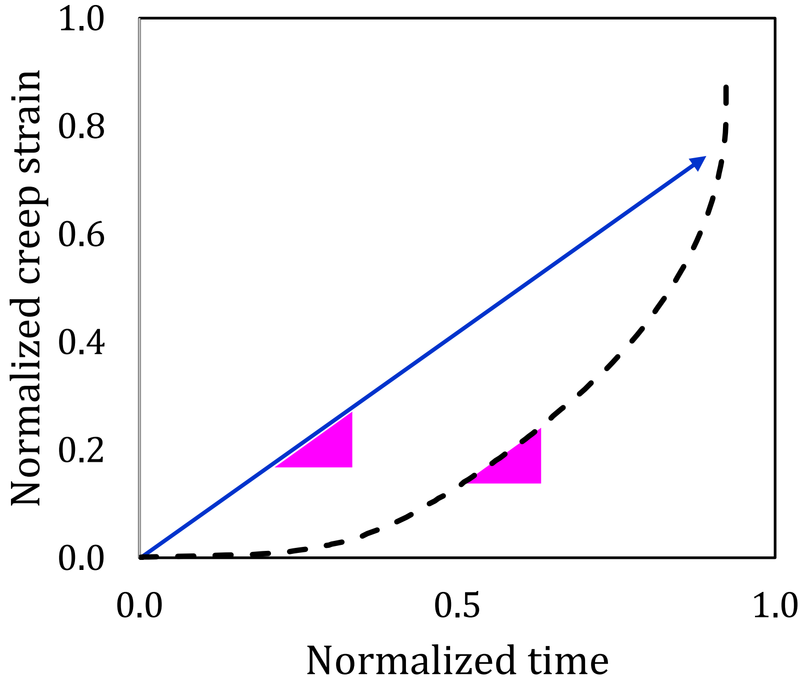
- Find suitable creep law
- Implement in our Finite Element code Lagamine[6]
- Validate for non-classical creep cases

[4]: E. El-Magd et al., *Met. And Mat. Trans. A*, 1994
[5]: B. Reichert et al., 1996, 1998, 1999
[6]: Code developed by MSM team, ULiège

Viscosity function $\dot{p} = f(\sigma, T, \ldots)$

Function development ⇆ Identification

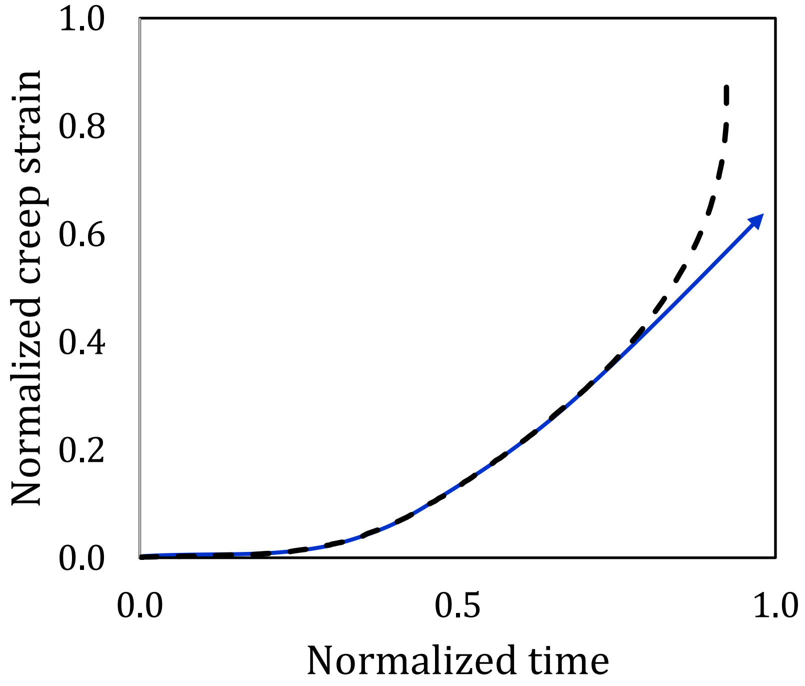
1. Prediction of the steady-state creep



$$\dot{p} = \left\langle \frac{\sigma_v}{K} \right\rangle^n$$

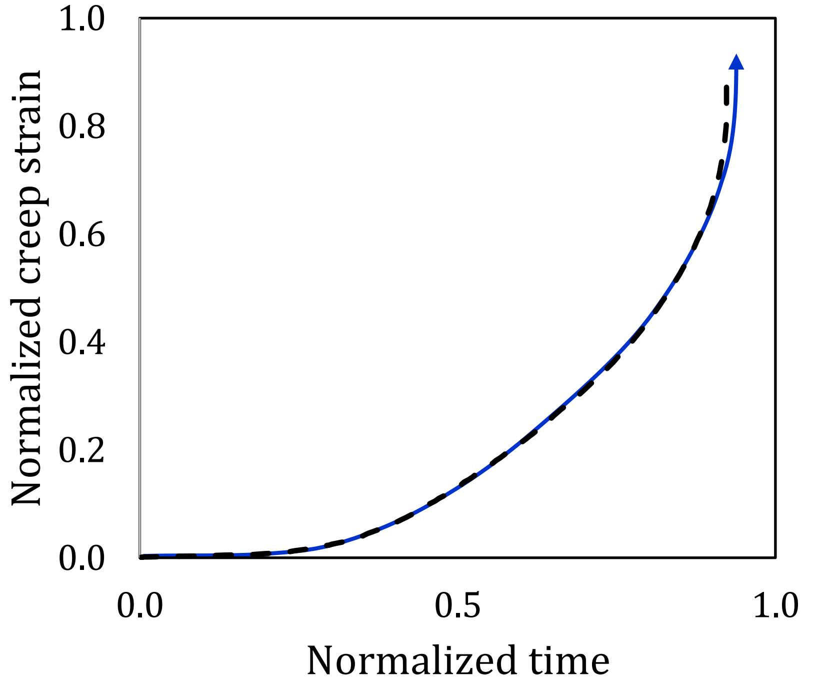
(Norton creep power law)

2. Prediction of the 1st peak



$$\dot{p} = something \times \text{Norton}$$

3. Damage & fracture



$$\tilde{\boldsymbol{\sigma}} = \left(\frac{\boldsymbol{\sigma}}{1 - D_{creep}} \right)$$

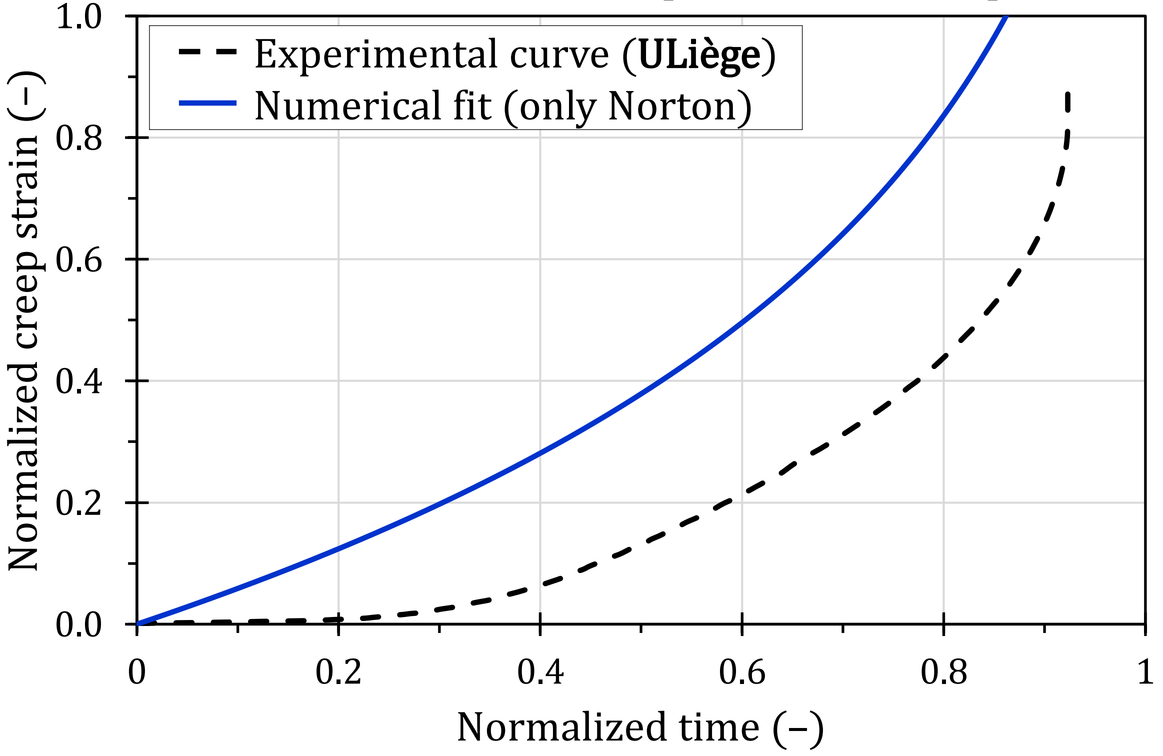
Viscosity function $\dot{p} = f(\sigma, T, \dots)$

Step 1. mcr2

$$\dot{p} = \left\langle \frac{\sigma_v}{K} \right\rangle^n$$

Prediction of steady-state creep rate (mcr2)

Normalized numerical – Experimental creep curves

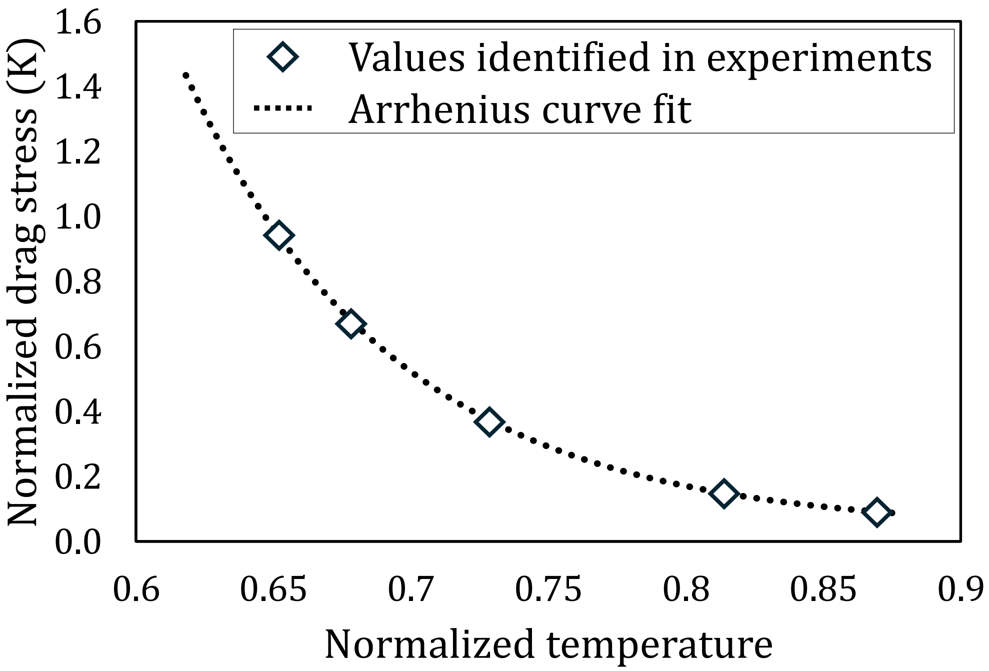


≫ σ_v = Overstress

≫ n is a constant

≫ K is identified as a single-Arrhenius function

$$K(T) = \mathrm{A}_K \left[1 - \mathrm{B}_K \exp\left(-\frac{\mathrm{C}_K}{T} \right) \right]$$



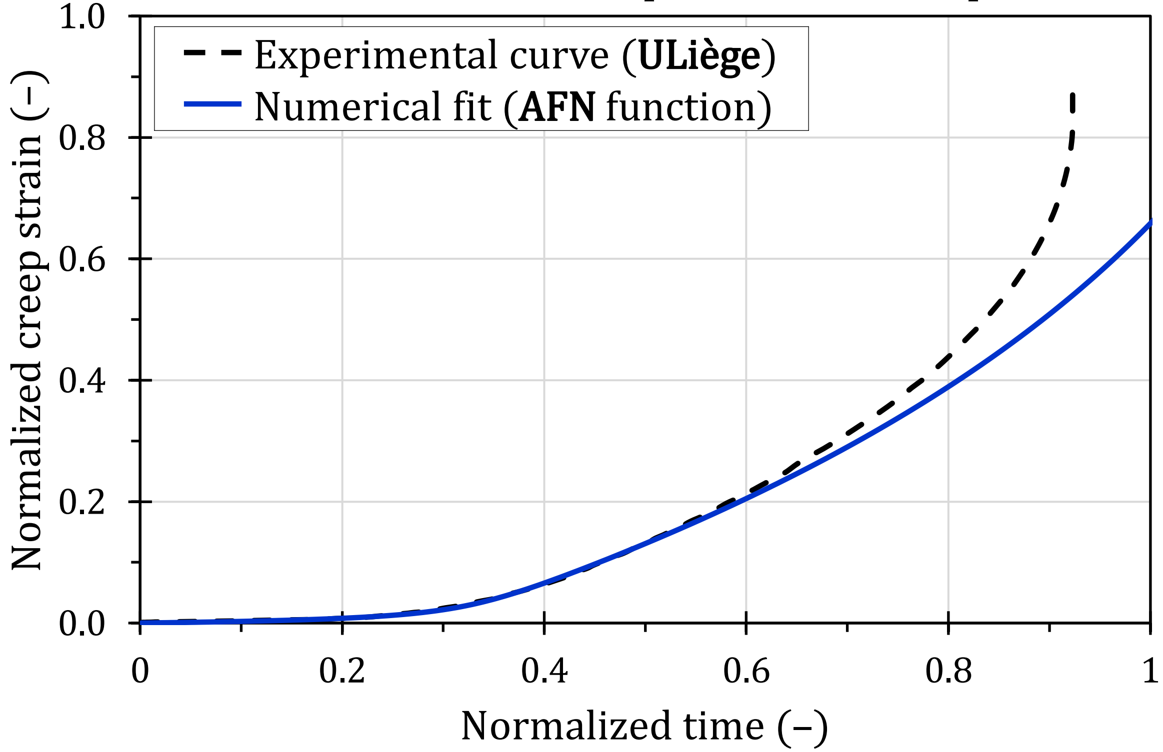
Viscosity function $\dot{p} = f(\sigma, T, \dots)$

Step 2. mcr1 + mcr2 = AFN

$$\dot{p} = \left\langle \frac{\sigma_v}{K(T)} \right\rangle^n \times \exp[-\mathbf{a} \times (p - \mathbf{b})^{-\mathbf{c}}]$$

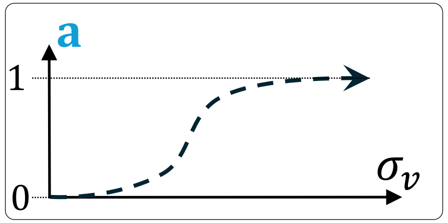
Prediction of full non-classical creep behavior

normalized numerical – Experimental creep curves

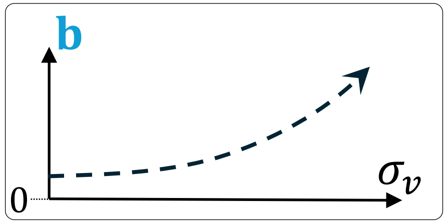


≫ Stress dependency of parameters (a, b, c)

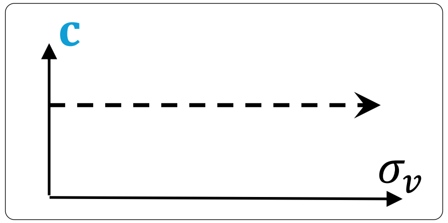
--> evaluated for a single temperature:



$$\mathbf{a}\big|_T = \frac{1}{1 + \exp(\sigma_v - a_2)}$$



$$\mathbf{b}\big|_T = b_1 + b_2 \exp(b_3 \cdot \sigma_v)$$

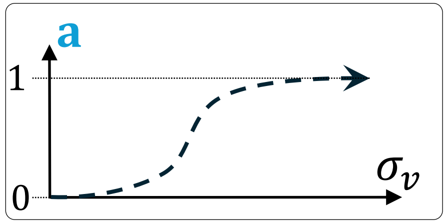


$$\mathbf{c} = constant$$

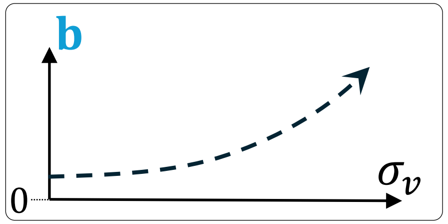
Step 2. mcr1 + mcr2

≫ Stress dependency of parameters (**a**, **b**, **c**)

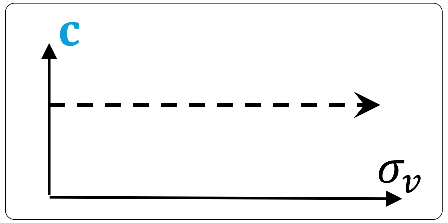
--> evaluated for a single temperature:



$$\mathbf{a} = \frac{1}{1 + \exp(\sigma_v - a_2)}$$



$$\mathbf{b}\big|_T = b_1 + b_2 \exp(b_3 \cdot \sigma_v)$$



$$\mathbf{c} = constant$$

≫ Temperature dependency

- $a_2(T) = x_1 \cdot T + x_2$ *(linear)*
- $b_3(T) = x_3 \cdot \exp(x_4 \cdot T)$ *(exponential)*

≫ Total number of parameters:

$\left\langle \dfrac{\sigma_v}{K(T)} \right\rangle^{n}$	Norton creep law	4
$e^{\frac{-1}{\mathbf{a}(p-\mathbf{b})^{\mathbf{c}}}}$	Activation Function	8
	Total	12

Step 3. Damage prediction

≫ Kachanov[7] damage law:

$$\dot{D}_{creep} = k_3 \left[\frac{\mathcal{Y}(\underline{\sigma}^d \cdot k_4)}{S_c} \right]^{S_{ce}} \cdot (1 - D_{creep})^{k_k}$$

≫ Implemented into our Lagamine FE code:

- Semi-coupled damage approach[8]

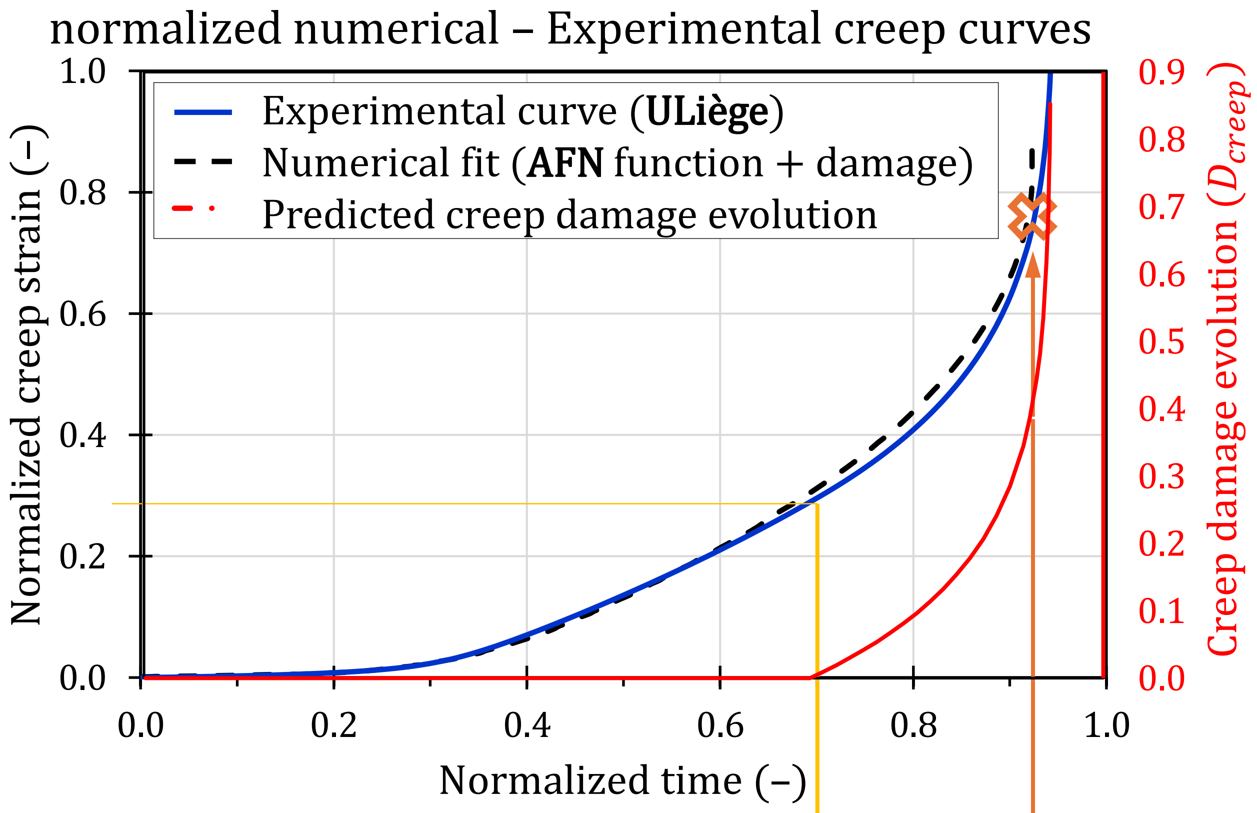
$$\tilde{\boldsymbol{\sigma}}^{k+1} = f(\sigma^{k+1}, D^k) \longrightarrow D^{k+1} = f(\sigma^{k+1}, \dots)$$

- Damage initiation criterion: critical creep strain

$$p_{critical} = f(T)$$

- Parameter optimization conducted by OPTIM[9]: optimization software for FE code, based on Levenberg-Marquardt algorithm

Prediction of the full creep curve



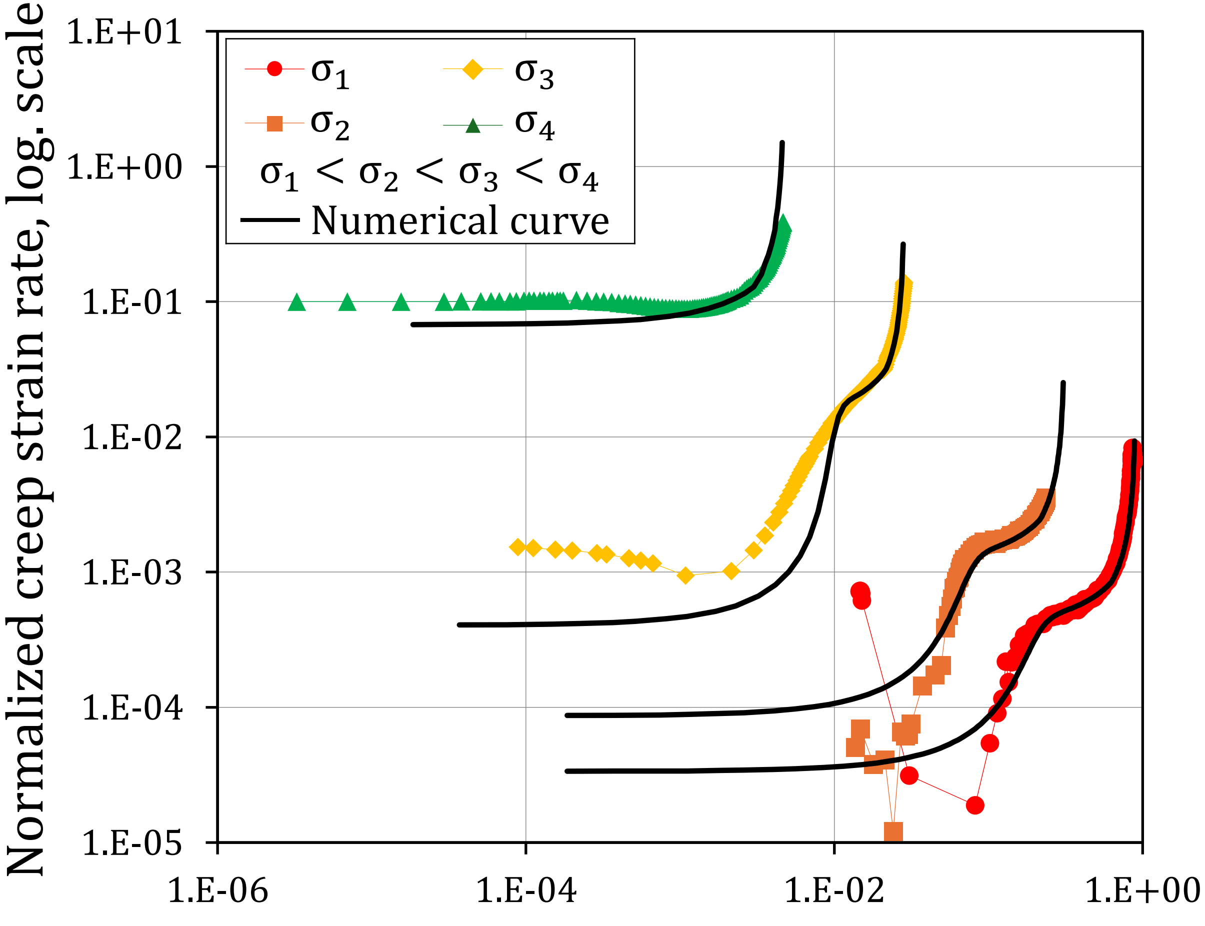
≫ Damage initiation criterion: $p_{critical}$

≫ Fracture criterion: $D_{frac} = const.$

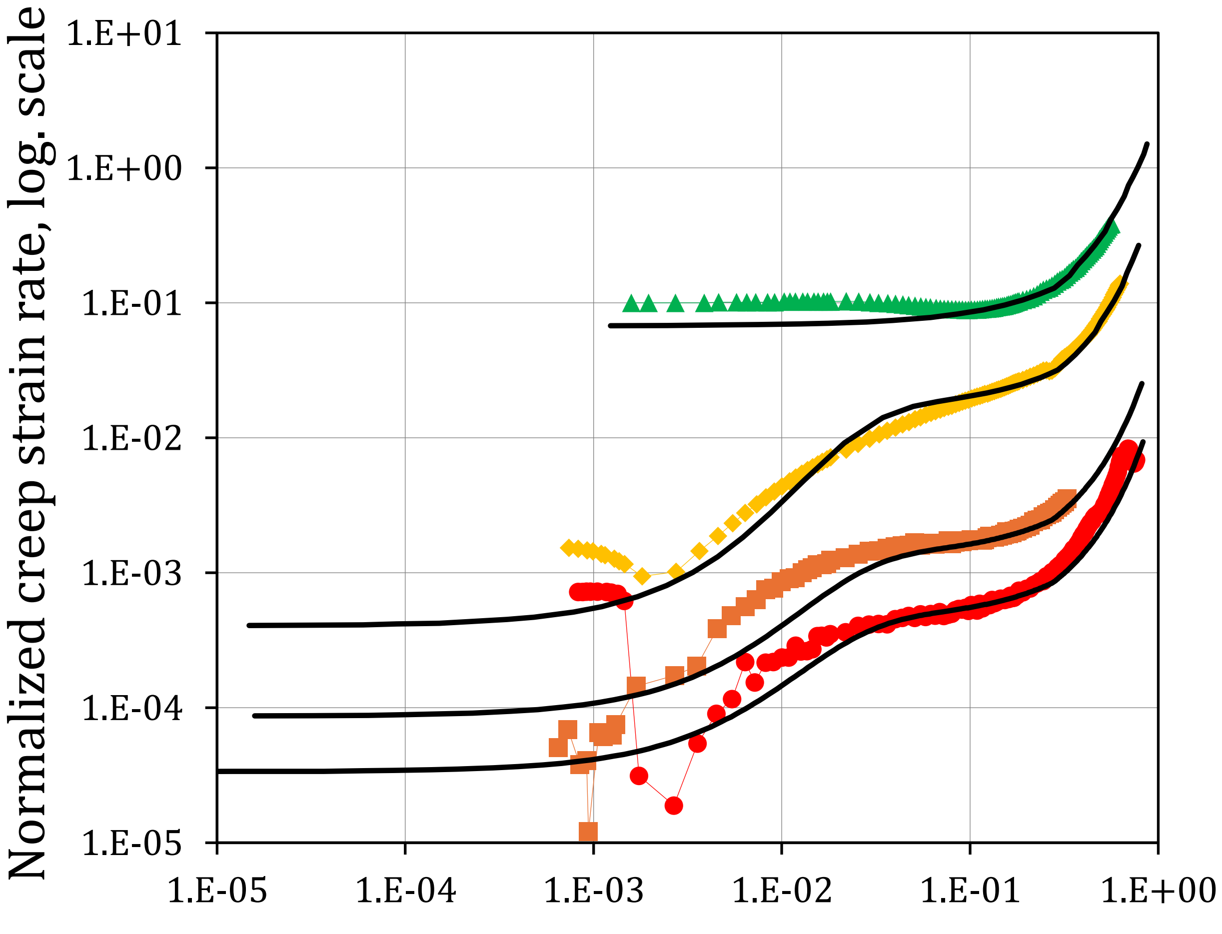
[7]: M. Kachanov, The Theory of Creep, Vol.1, 1967.
[8]: H. Morch, PhD. Thesis, ULiège, 2021.
[9]: E. Bettaieb et al., *IJMF*, 2022.

Validation of macromechanical law

Creep strain rate v/s time prediction
normalized numerical – Experimental creep curves



Creep strain rate v/s creep strain prediction
normalized numerical – Experimental creep curves

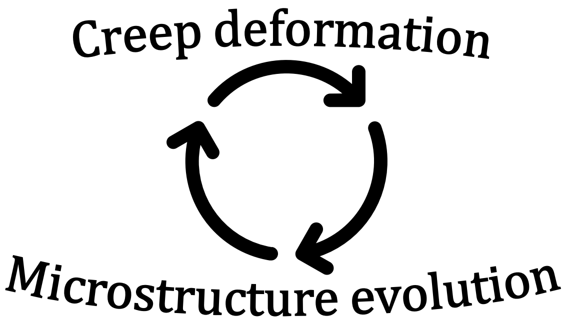


Concluding remarks & future work

- ✓ Developed **reliable** and **simple** approach to model non-classical creep
- ✓ Implemented in finite element code --> computationally efficient
- ✓ **Applied** and **validated** to predict creep & fracture of **800H** alloy

...the validation of macromechanical law does have some limitations:

- ➢ Available experimental data
  - High-temperature low-stress creep tests are long & expensive
- ➢ Non-classical creep response is affected by
  - Initial microstructure (Heat treatment, processing, manufacturing)
  - Aging (precipitate ripening & coarsening)



Solution proposed:

- ➢ Implementation of micro-scale creep model ⟶ Mean-field approach[10–12]
  - ↳ Execution of Virtual tests
    - ↳ Generate reliable & accurate creep curves
      - ↳ Further identify & validate finite element model

10: N.M. Ghoniem et al., *Res Mechanica*, 1990.
11: F. Riedlsperger et al., 2020, 2022, 2023,...
12: CreeSo software (JKU, see imk.jku.at/creeso)

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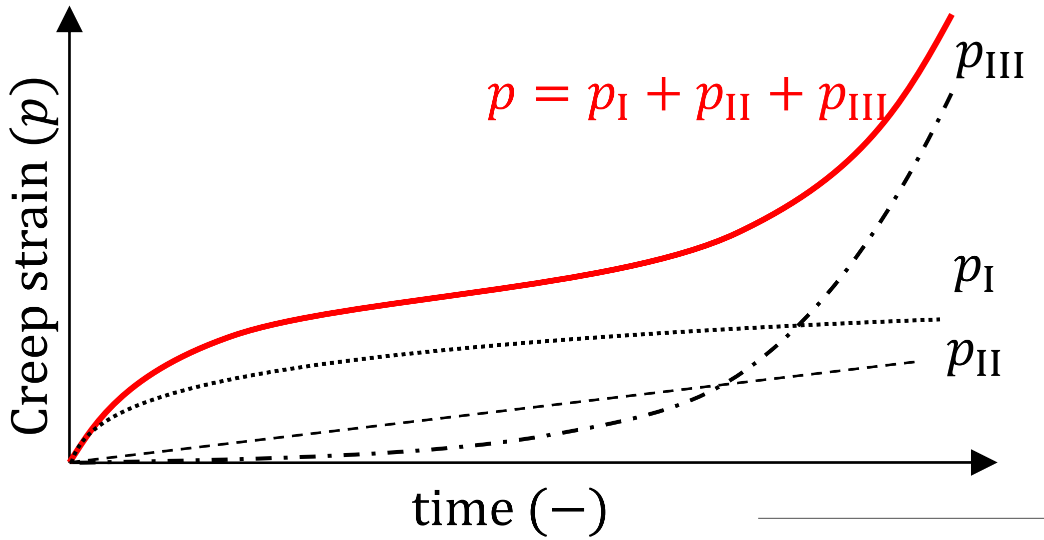
Macromechanical modeling of creep

- Precedent[A1]: Graham-Walles function

Model type:	Graham-Walles (empirical)
Pros:	· Very versatile
Cons:	· Large scale difference between params · Large nb. of params (difficult identification)



$$\dot{p} = \sum_{i=1}^{j} A_i \exp\left(\frac{-C}{T}\right) \sigma_{eq}^{m}\, p^{n} \longrightarrow$$

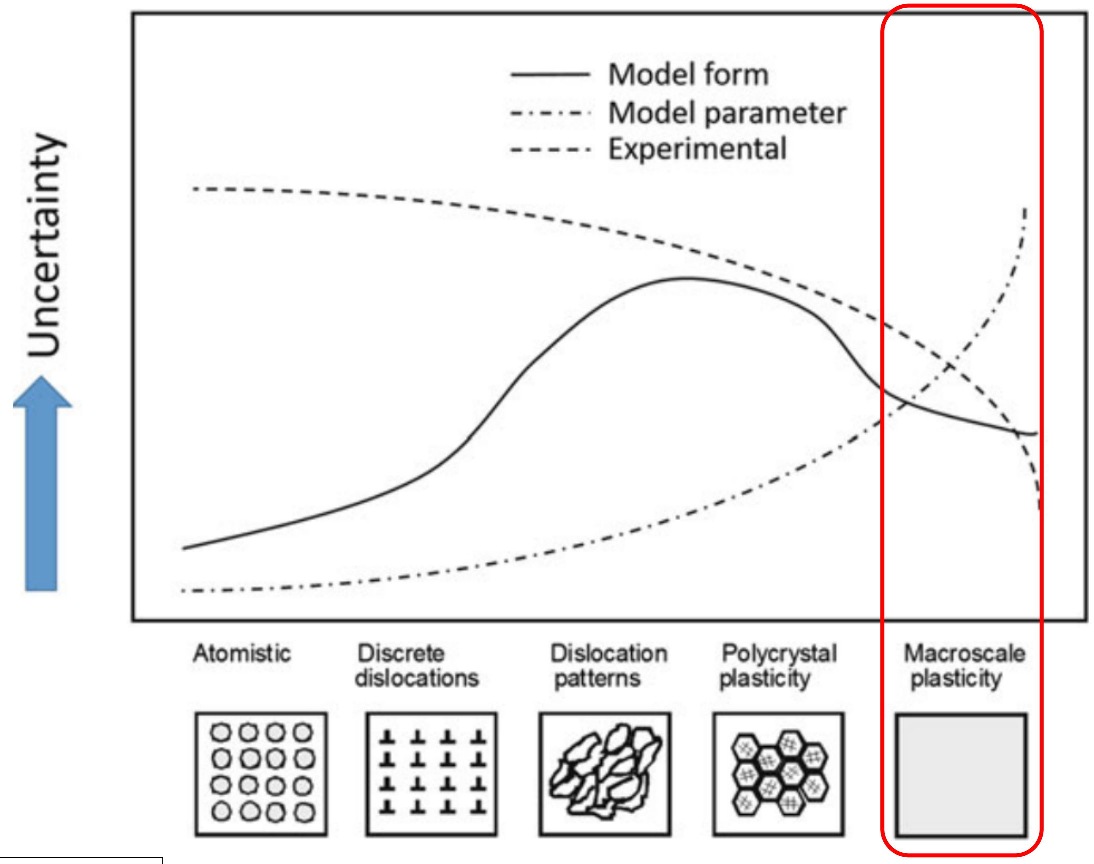
4 parameters per curve

Difficult parameter fitting

Huge non-linearity $\dot{p} = f(\sigma, T, p, \ldots)$

[A1]: C. Rojas-Ulloa et al., *CAMWA*, 2024

Let's find balance[A2]

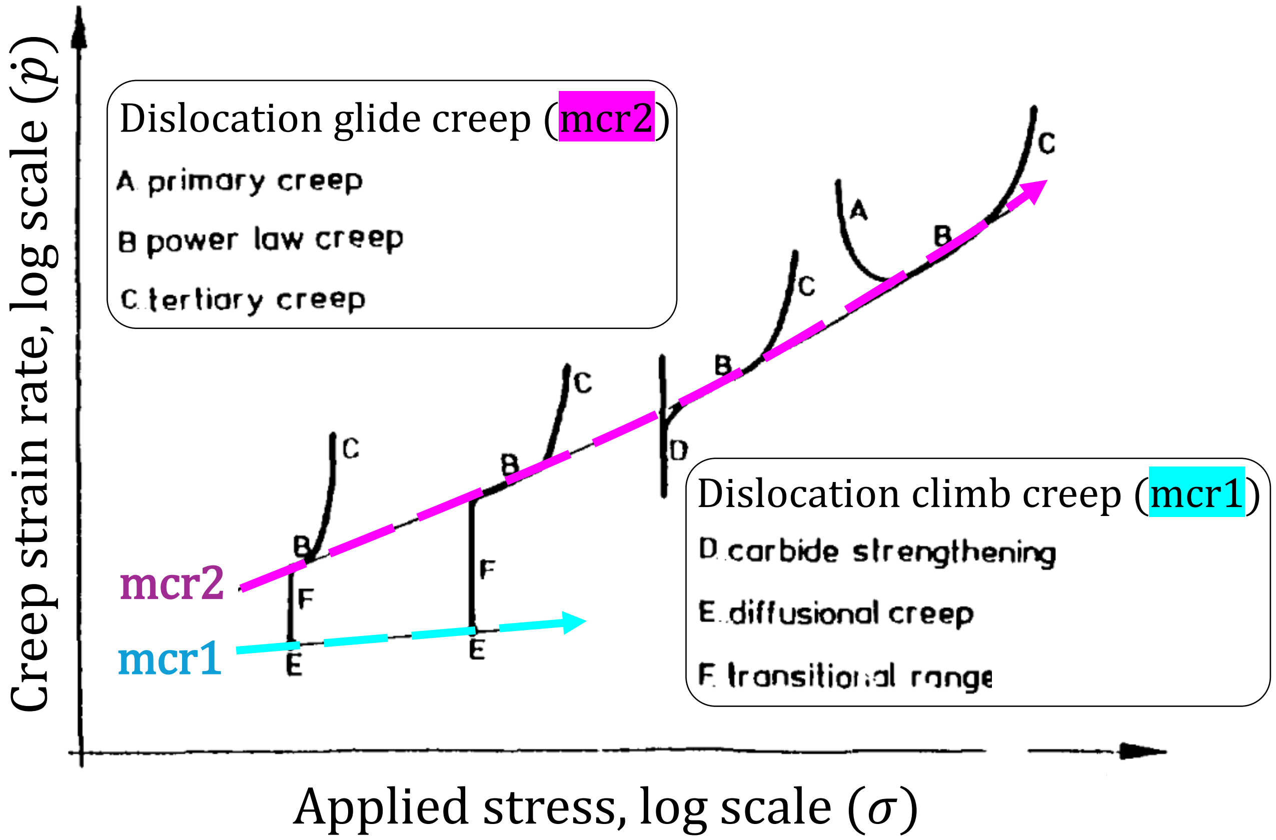


[A2]: Figure after (David L. McDowell,, S. Mesarovic et al. (eds.), Mesoscale Models, Springer, 2019)

Non-classical creep overview

Non-classical creep response

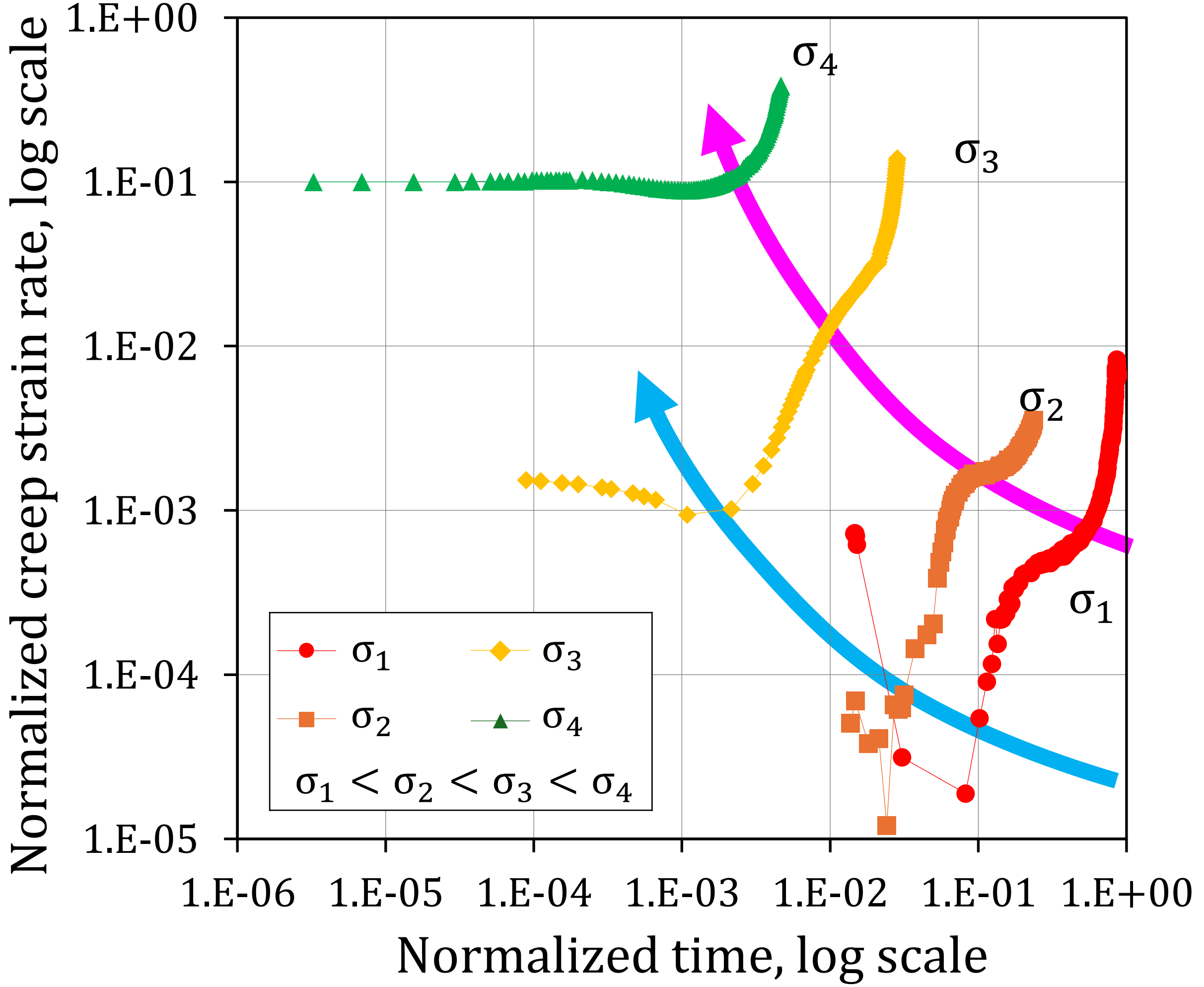
Qualitative ($\dot{p}-\sigma$) mapping of the two creep strain rate minima (mcr1 and mcr2) in Incoloy 800H at 800ºC [A3]



A3: Figure adapetd from (K.Spiradek et al., *Materials Science*, 1989)

...observed in ULiège

Superposition of creep test curves on 800H
for a single (high) temperature



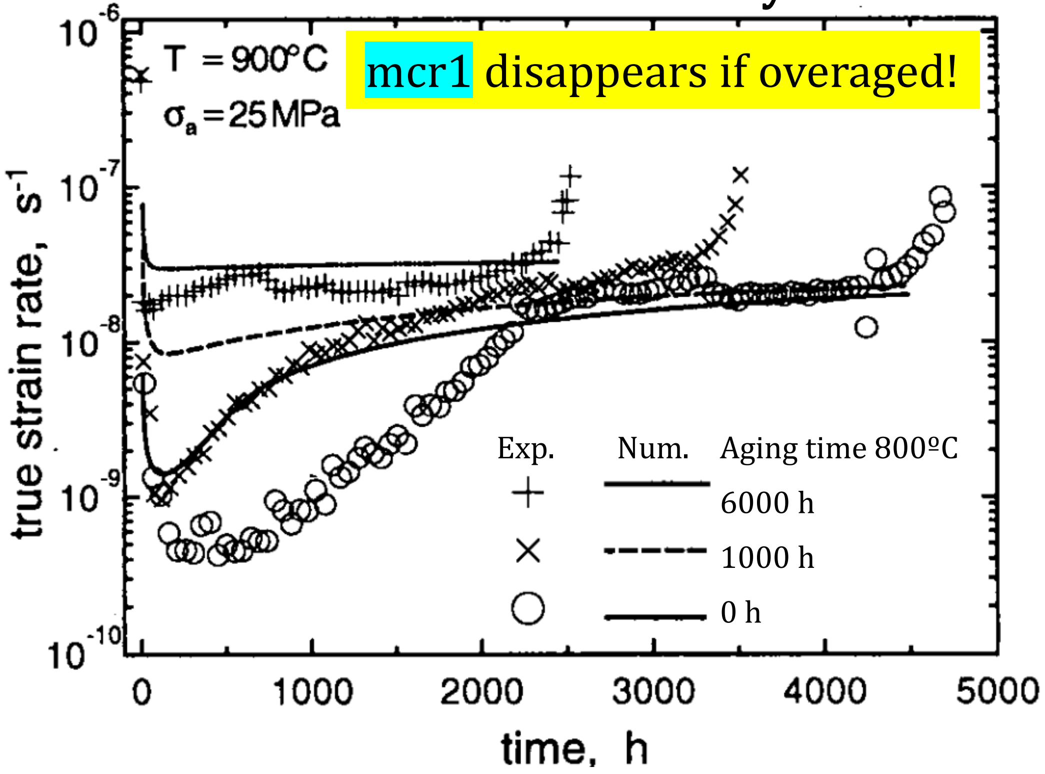
Non-classical modeling in literature

- (B. Reichert et al., 1996, 1998, 1999)

Model type:	“One-parameter” (semi-physical, analytical)
Pros:	Accurate precipitate dependency
Cons:	Limited applicability, parameter uncertainty

Validation on 800H alloy

mcr1 disappears if overaged!

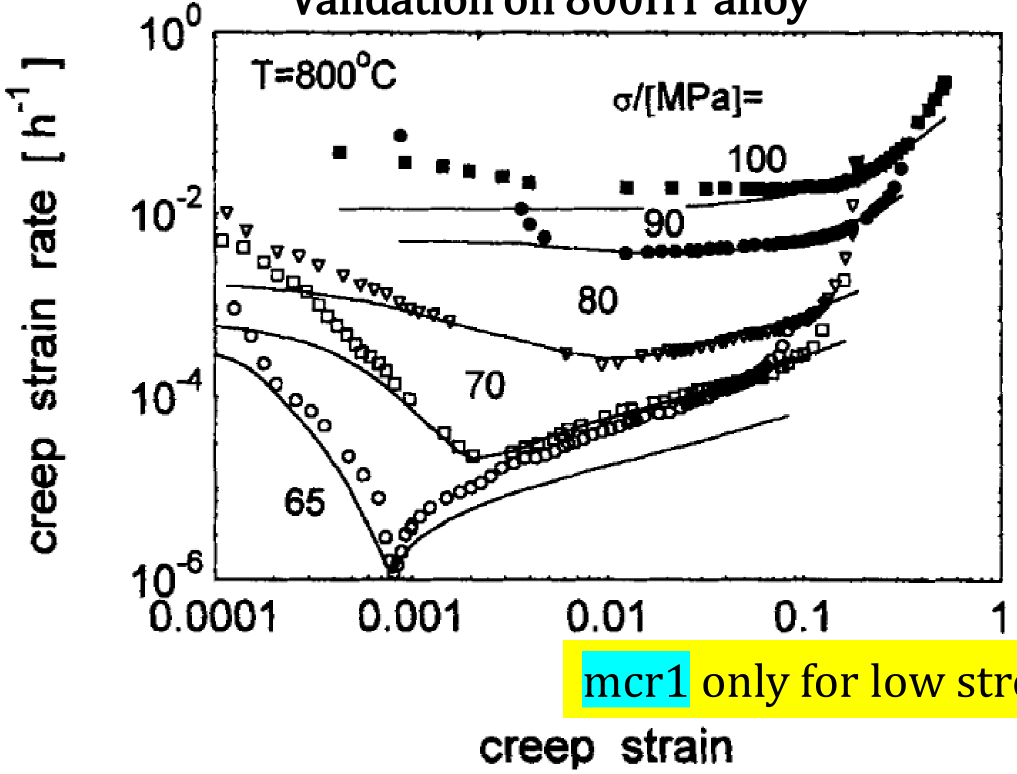


(B. Reichert et al., *Materials Technology*, 1999)

- (E. El-Magd et al., 1994)

Model type:	Modified Norton-Bailey (Empirical, analytical)
Pros:	Precipitate dependency (empirical)
Cons:	Limited applicability, parameter uncertainty

Validation on 800HT alloy



mcr1 only for low stresses!

(E. El-Magd et al., *Met. And Mat. Trans. A*, 1994)