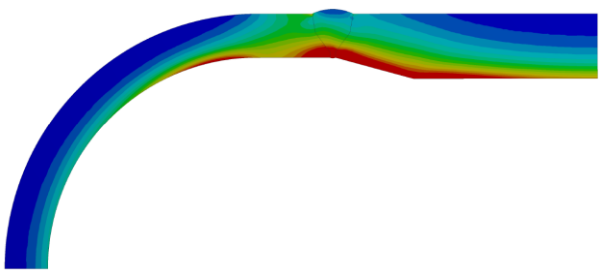
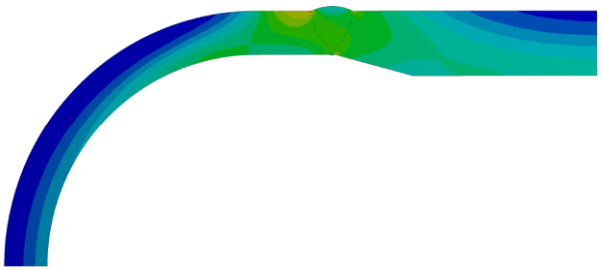
EFFECTS OF PRIMARY AND SECONDARY CREEP FORMULATION ON API 579-1 RESIDUAL LIFE EVALUATION

Lorenzo Scano, Ph.D.
Studio Scano Associato
Safety & Integrity
Piazzale Chiavris, 66
33100 – Udine, ITALY (EU)

Prof. Luca Esposito
University of Naples «Federico II»
Department of Industrial Engineering
Piazzale Tecchio, 80
80125 – Naples, ITALY (EU)





SUMMARY

- Creep: culprit for pressure equipment failure at high temperatures
- Creep damage evaluation: FEA and FFS, e.g., API 579-1 Sec. 10
- **Only secondary creep "typically" assessed and only dislocational aspects**
- First step of research (2017): **diffusion impact on creep life:**
  - Case study: HRSG assembly ASTM A335 P22 components
  - Secondary creep **only**
  - Different constitutive equations accounting for diffusive processes
  - Creep life: API 579-1/LMP, Monkman-Grant, ductility exhaustion

SUMMARY

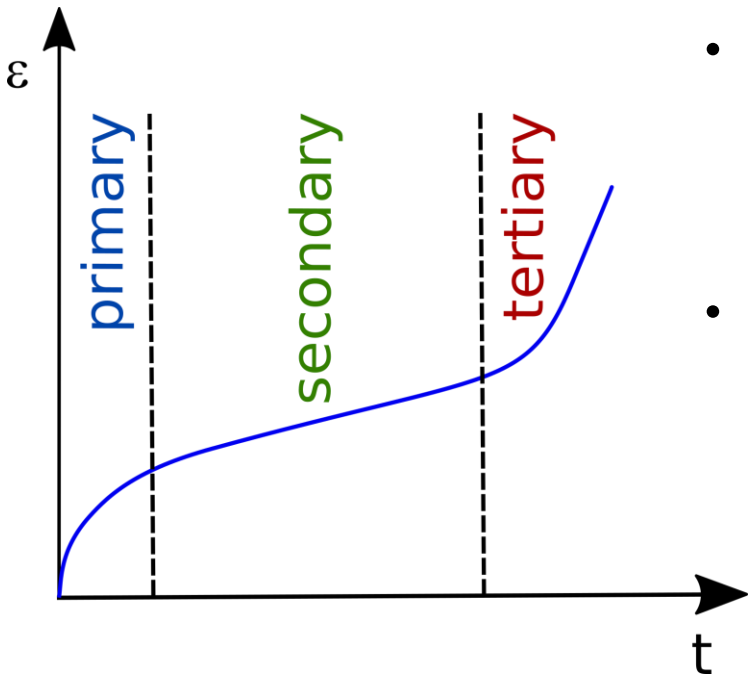
- Neglecting diffusive processes: **non-conservative** (low stresses, relaxation points)

- In this work: analysis extended to **primary creep**, results compared to API 579-1/Omega

- Steps of analysis:

  - **Primary+secondary creep formulation**
  - FEA with custom material models and Omega method implementation (ANSYS software)
  - Comparison: secondary vs. primary+secondary creep, dislocational and diffusive+dislocational
  - Comparison: secondary/primary+secondary API 579-1/LMP vs. API 579-1/Omega

THE CREEP PHENOMENON



Secondary creep typically dominant for long-term exposures of pressure equipment at high temperatures!

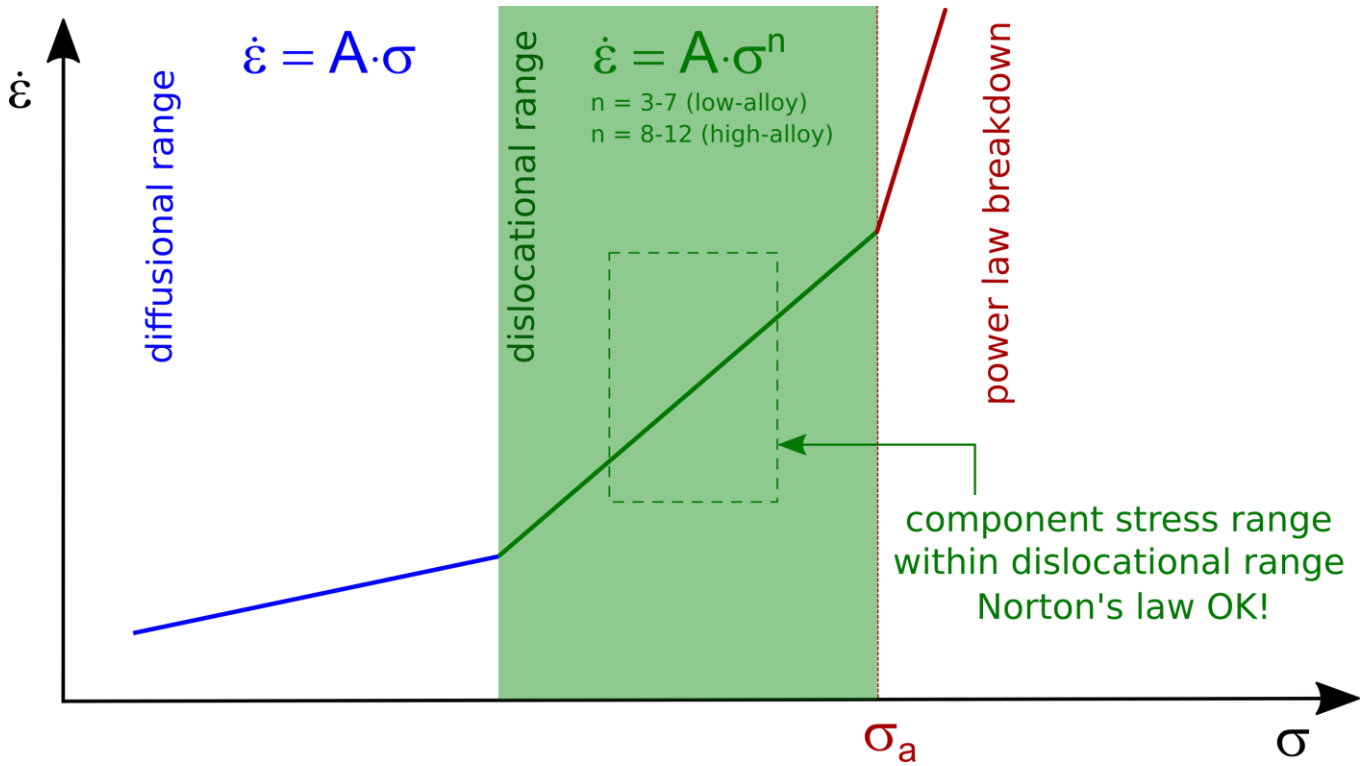
- Creep: <u>thermally-activated process,</u> time-dependent, progressive plastic strain, T > 0.3-0.4 $T_{homologous}$
- Three creep stages:
  - PRIMARY: decrease of strain rate due to strain-hardening
  - SECONDARY: constant strain rate, softening processes balance dislocation pile-up
  - TERTIARY: increase of strain rate, actual damage, crack and failure

THE CREEP PHENOMENON

- Creep: heterogeneous phenomenon involving two processes:
  - DIFFUSION:
    - Thermally-activated formation and migration of vacancies within material lattice
    - Low-stress range at low (Coble creep) and high (Nabarro-Herring creep) temperatures
    - **Secondary creep formulation → linear: $d\varepsilon/dt = A \cdot \sigma$**
  - DISLOCATION GLIDE+CLIMB:
    - Major contribute to plastic strain. Dislocations move through slipping planes and <u>can pass through obstacles, i.e., particles or other dislocations (CLIMBING), with diffusion aid</u>
    - High-stress range below athermal yield stress
    - **Secondary creep formulation → power law (PL): $d\varepsilon/dt = A \cdot \sigma^n$**

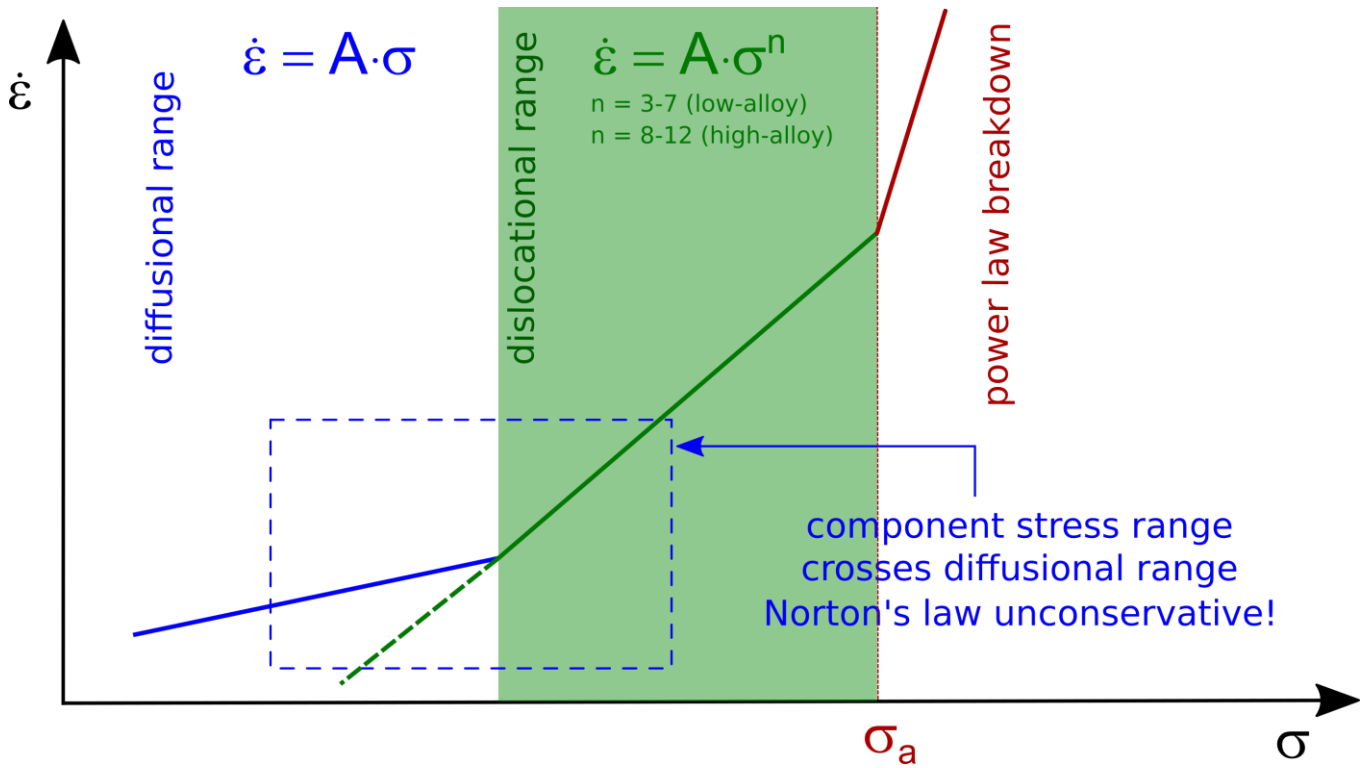
FIRST STEP (2017): SECONDARY CREEP FORMULATIONS

- For PVP applications (long exposures):
  - Steady-state creep only (primary negligible)
  - Only dislocational processes (Norton's law)



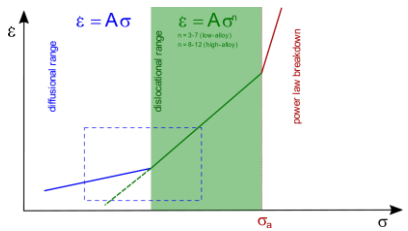
FIRST STEP (2017): SECONDARY CREEP FORMULATIONS

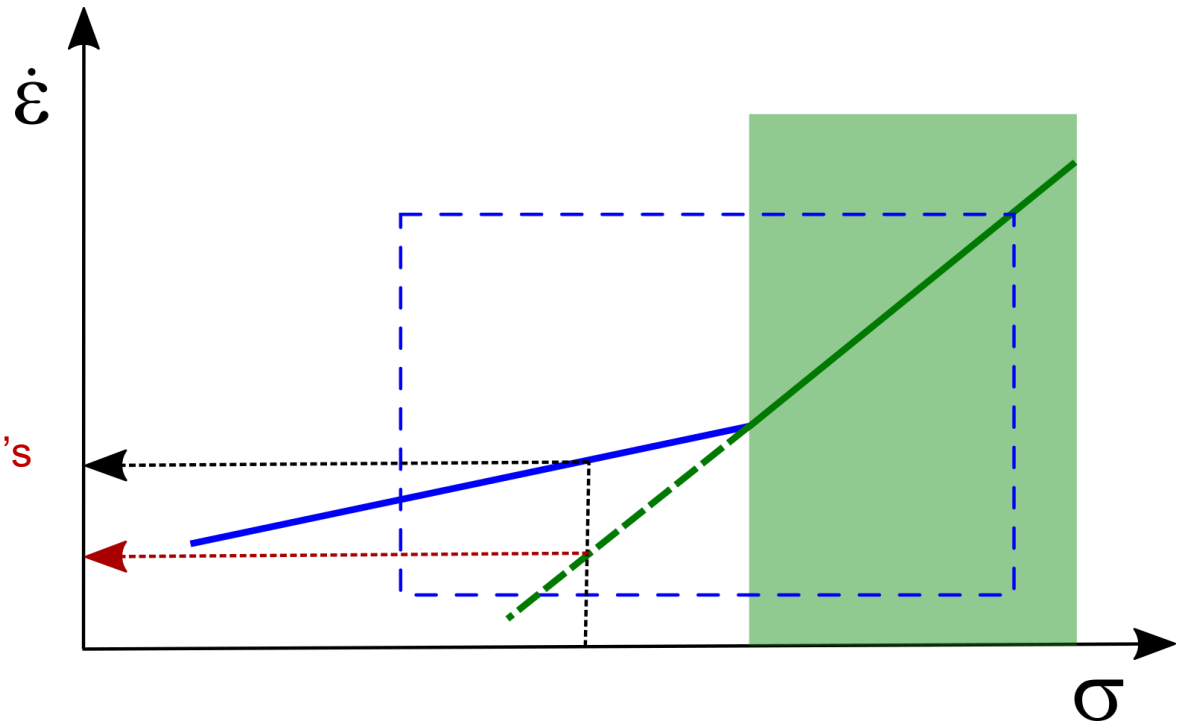
- Extrapolating application of Norton's law (n > 3) into diffusive regime (n = 1): **unconservative**!



FIRST STEP (2017): SECONDARY CREEP FORMULATIONS

- Extrapolating application of Norton's law (n > 3) into diffusive regime (n = 1): **unconservative**!

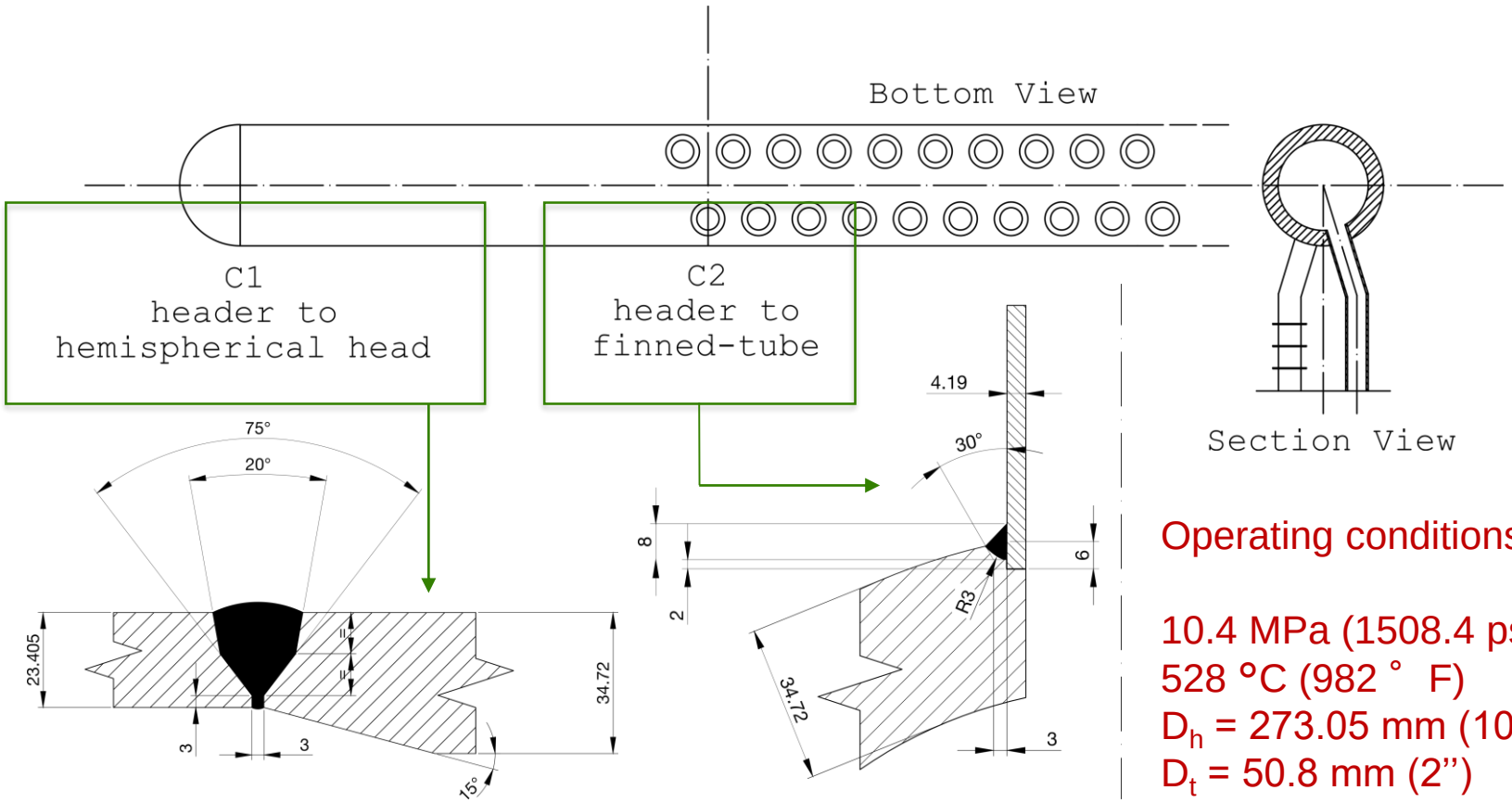




Same stress, Norton's law predicted strain rate **lower**!

CASE STUDY

- ASTM A335 P22 HRSG header: two components investigated



Operating conditions:

10.4 MPa (1508.4 psi)
528 °C (982 ° F)
D_h = 273.05 mm (10”)
D_t = 50.8 mm (2”)

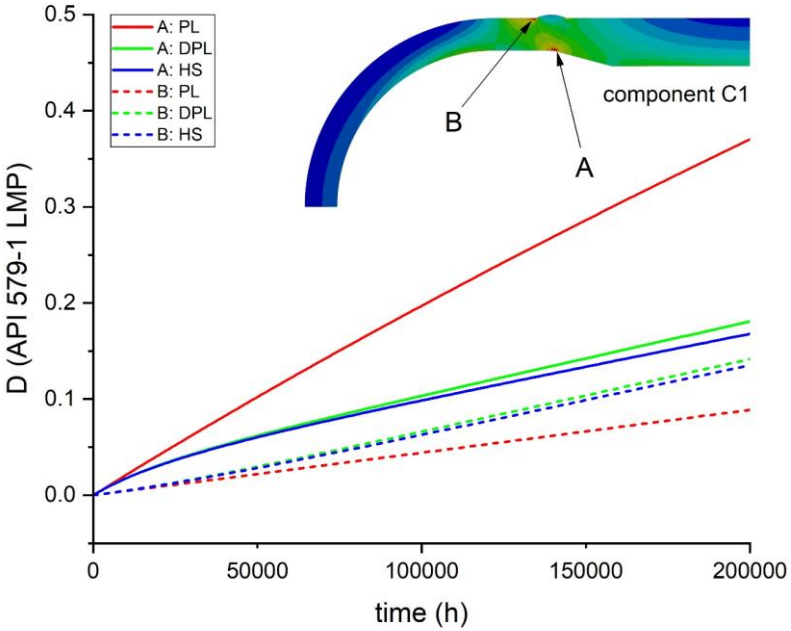
FIRST STEP (2017): RESULTS

- Three secondary creep formulations:
  - Norton's power-law (PL, dislocational creep)
  - Double power-law (DPL, diffusive+dislocational creep)
  - Garofolo's hyperbolic sine (HS, diffusive+dislocational creep)

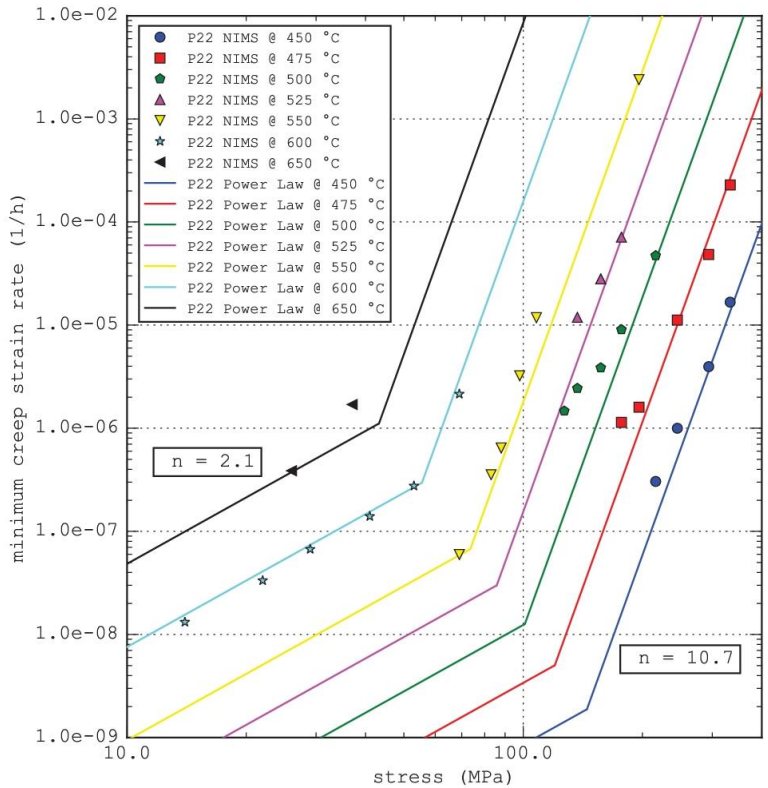
- Time-to-rupture according to:
  - API 579-1/LMP
  - Monkman-Grant
  - Ductility-exhaustion (DE)

- API 579-1/LMP:
  - High-stress: PL conservative (stress relaxation)
  - Low-stress: PL non-conservative (stress redistribution)

- Monkman-Grant and DE:
  - PL non-conservative (higher strain accumulation)



MATERIAL DATA AND SECONDARY CREEP FORMULATION



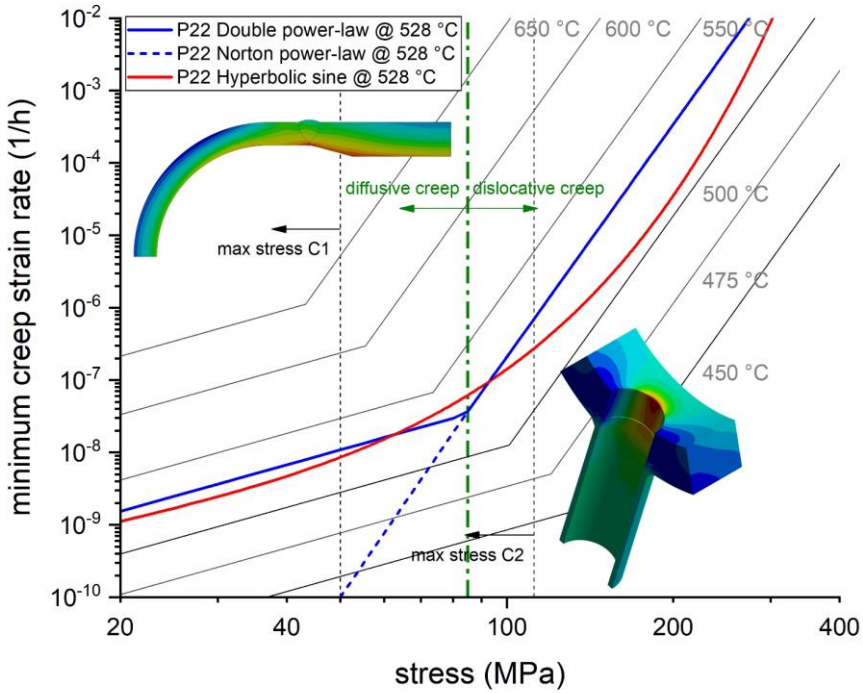
- ASTM A335 P22 (annealed)
- NIMS database data
- Temperature range: 450 – 650 °C
- Data interpolated using a PL equation:

$$d\varepsilon/dt = A \cdot e^{-Q/RT} \cdot \sigma^n$$

- Diffusional and dislocational regimes evident at low and high stresses:

	Diffusional creep	Dislocational creep
A =	$4.17 \cdot 10^4$	$7.20 \cdot 10^6$
Q =	249 kJ/mol	535 kJ/mol
n =	2.14	10.70

MATERIAL DATA AND SECONDARY CREEP FORMULATION



- Experimental data extrapolated at operating T = 528 °C
- 3 secondary creep formulations:
  - Standard Norton's PL:
    $d\varepsilon/dt = A \cdot \sigma^n$ (n = 10.7)
  - Double PL (DPL) including diffusion:
    $d\varepsilon/dt = A \cdot \sigma^n$ (n = 10.7)
    $d\varepsilon/dt = A \cdot \sigma^n$ (n = 2.14)
  - Sinh Garofolo's equation:
    $d\varepsilon/dt = B \cdot (\sinh(C \cdot \sigma))^n$

Aim of present work: **including primary creep modeling!**

PRIMARY CREEP MODELING

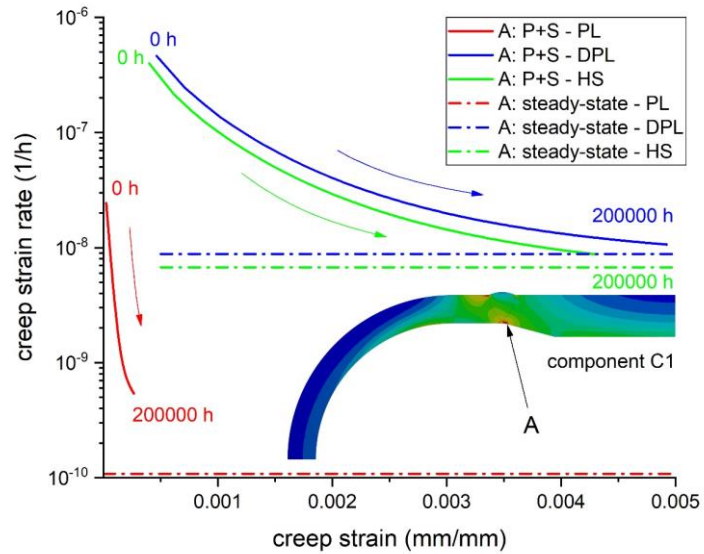
- Primary creep <u>modeled through saturating hardening function</u> (HF):

$$HF(\sigma, \varepsilon_c, \mathrm{T}) = \exp\left(\frac{P_1 \cdot \sigma \cdot e^{-\varepsilon_c/P_2}}{RT}\right)$$

$$P_1 = \frac{K_a}{1 + e^{K_b(\sigma - K_c)}} \qquad P_2 = \frac{1 + e^{K_e(\sigma - K_f)}}{K_d}$$

- $P_{1/2}$ → activation volume/decay functions
- K_* → material parameters
- Material constants calculated scaling parameters previously identified for ASTM A335 P91 (Esposito et al., 2013)

K_a	K_b	K_c	K_d	K_e	K_f
2000	0.0221	30.9	1700	0.01715	28

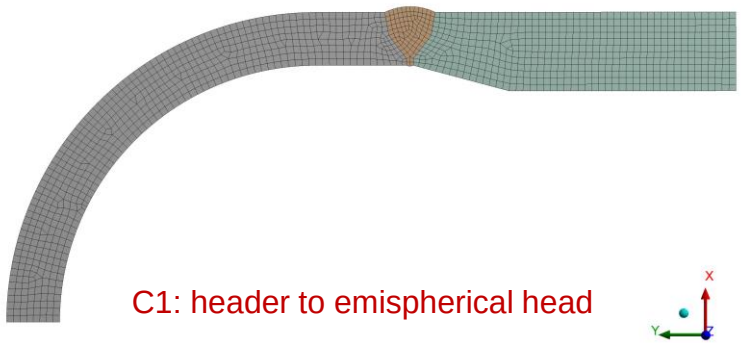


Primary+secondary formulations:

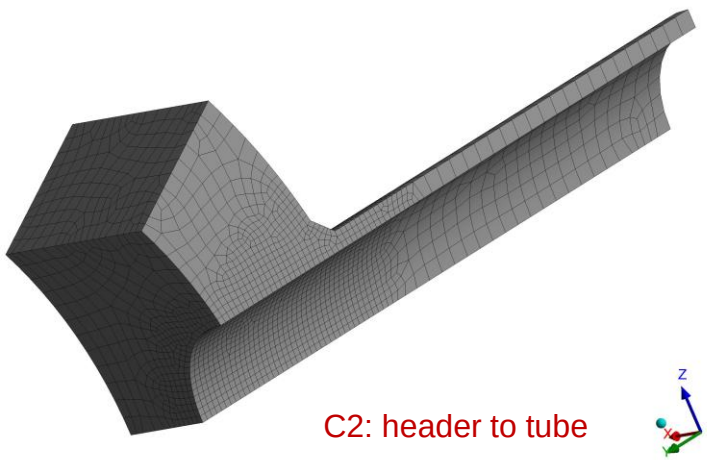
$d\varepsilon/dt = HF \cdot A \cdot \sigma^n$

$d\varepsilon/dt = HF \cdot B \cdot (\sinh(C \cdot \sigma))^n$

FINITE ELEMENTS INELASTIC ANALYSIS



C1: header to emispherical head



C2: header to tube

- ANSYS FE software with custom creep models (user-subroutines)
- FE shell/axisymmetric (C1) and solid hexahedral (C2) elements
- Inelastic analysis with creep and plasticity from 0 to 200000 h
- API 579-1 creep damage D <u>at every integration step</u>:

$$D = \sum_i \frac{t_i}{L_i}$$

$$L_i = 10^{\frac{1000 \cdot LMP(S_{e,i})}{T+460} - C_{LMP}}$$

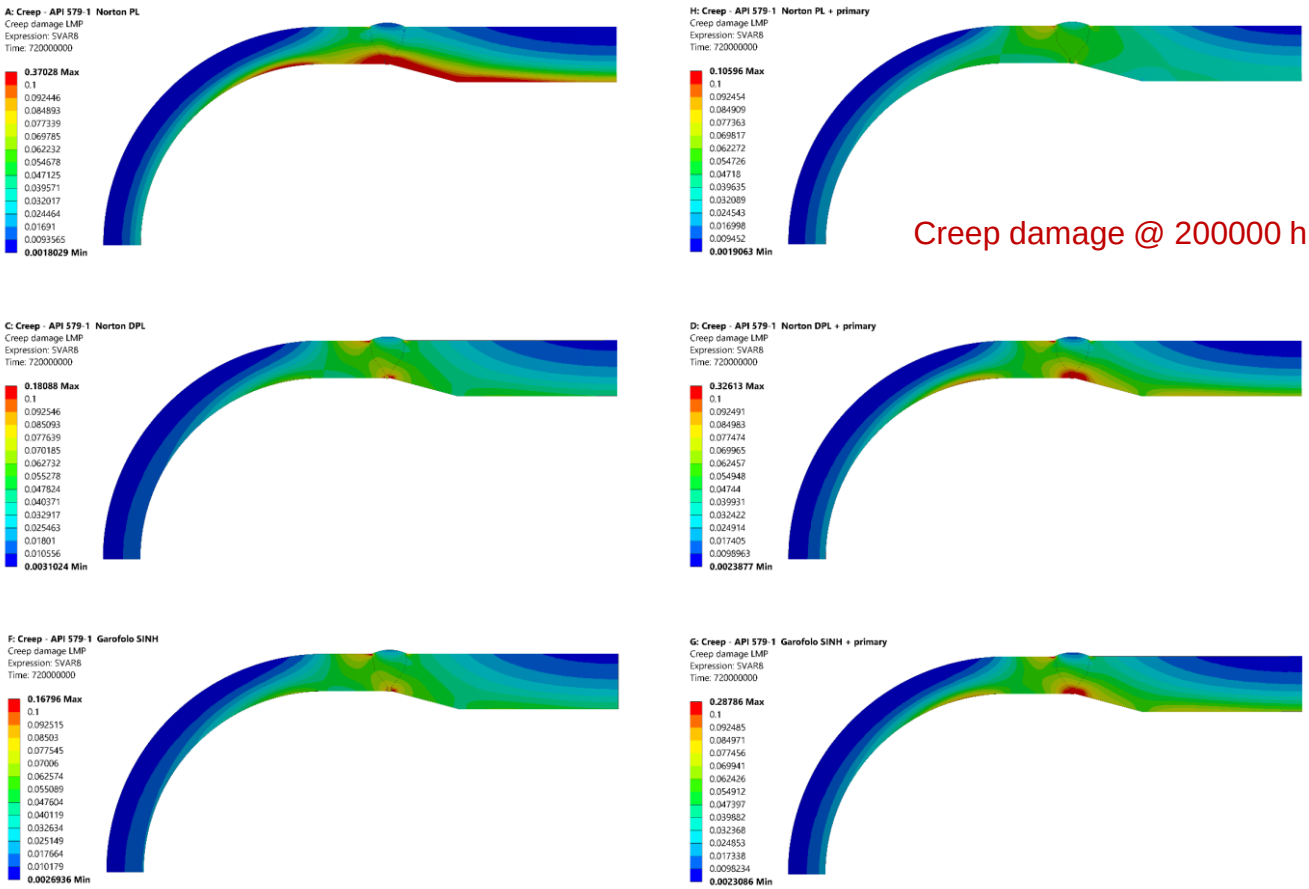
$$S_{e,i} = \sigma_{VM,i}\, e^{\left[0.24 \cdot \left(\frac{J_1}{S_s} - 1\right)\right]}$$

$$J_{1,i} = \sigma_1 + \sigma_2 + \sigma_3$$

$$S_{s,i} = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2}$$

- Constitutive equations:
  - Secondary only (PL, DPL, SINH)
  - Primary+secondary (PL, DPL, SINH)

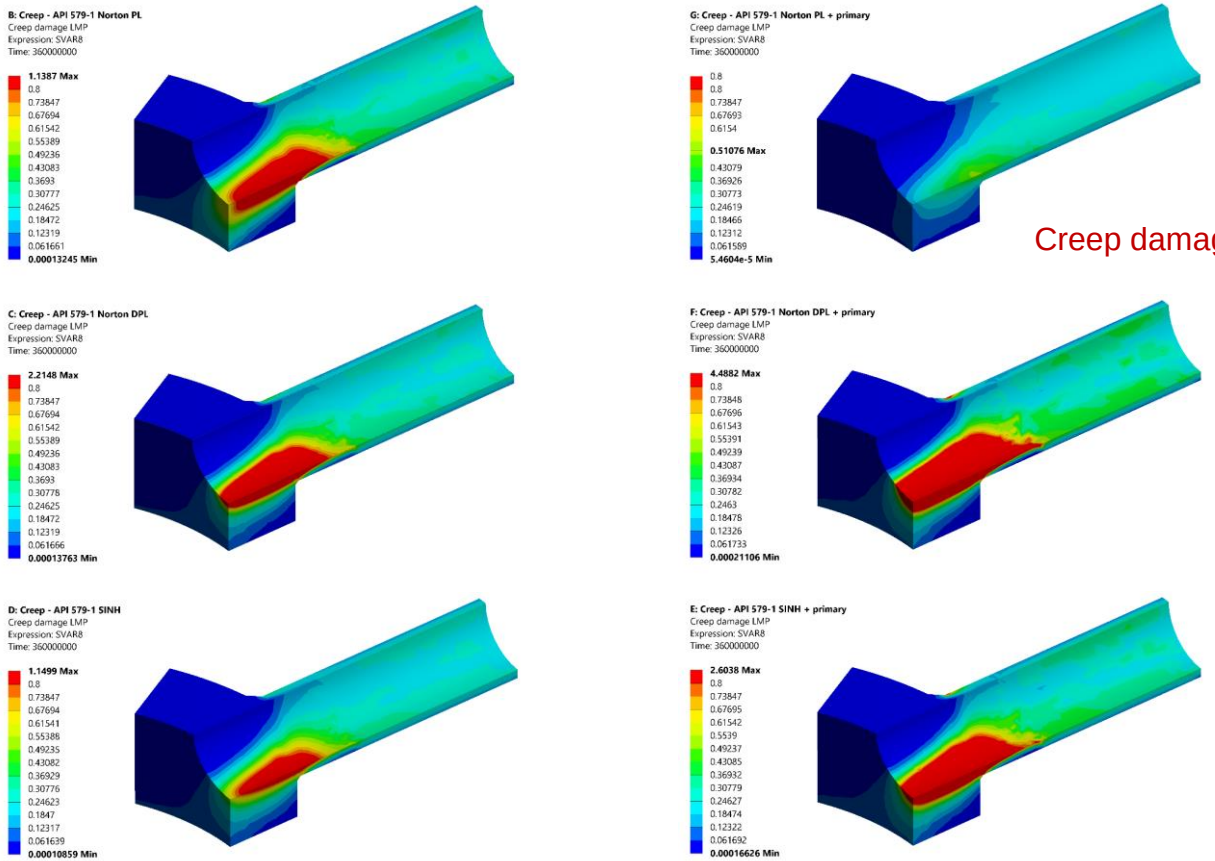
FINITE ELEMENTS INELASTIC ANALYSIS



C1: Norton's PL → Creep damage decreases with primary creep modeled

C1: DPL/SINH Creep damage increases with primary creep modeled

FINITE ELEMENTS INELASTIC ANALYSIS

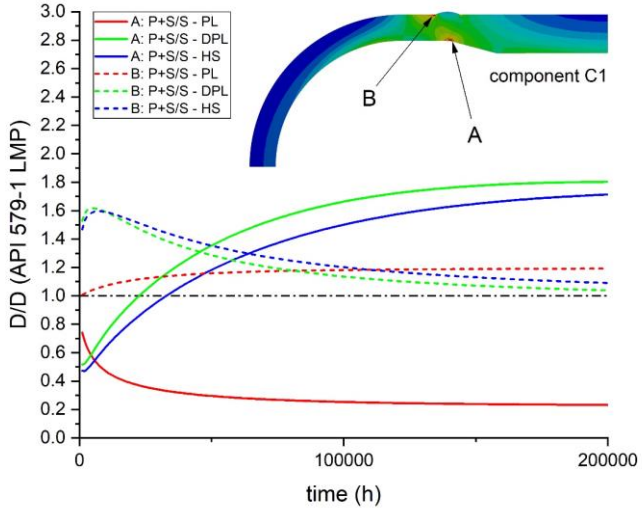


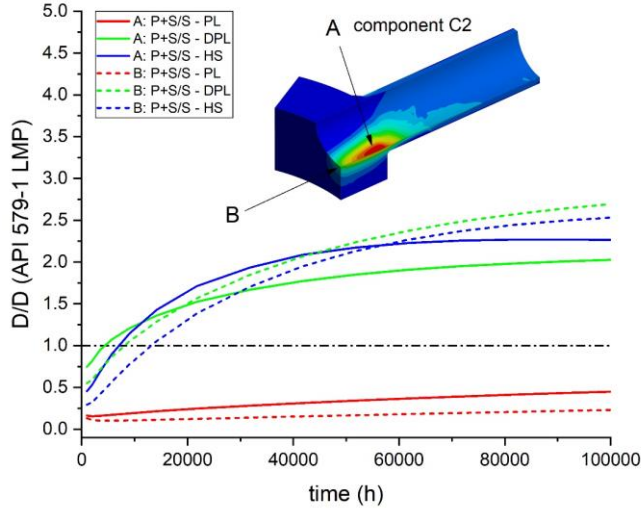
Creep damage @ 200000 h

C2: Norton's PL → Creep damage decreases with primary creep modeled

C2: DPL/SINH Creep damage increases with primary creep modeled

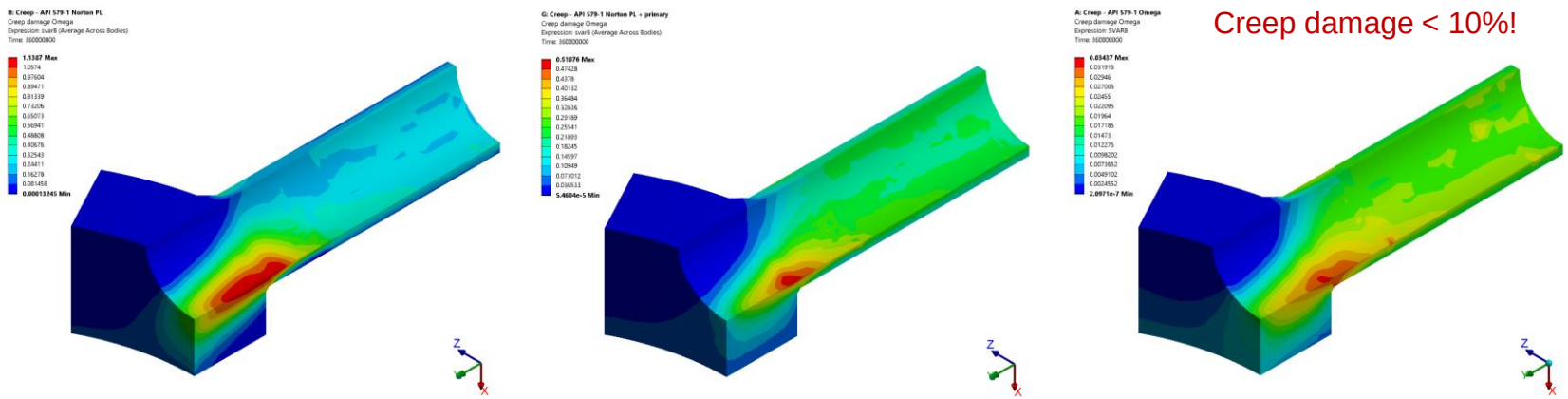
SECONDARY CREEP VS. PRIMARY+SECONDARY CREEP





- Stress concentrations (C1-A, C2-A/B):
  - Maximum D (API 579-1, D = f(σ))
  - Primary stage <u>increases</u> D with DPL/HS
  - Primary stage <u>decreases</u> D with PL
- Stress redistribution points (C1-B):
  - Primary stage <u>always increases</u> D
- Secondary creep Norton's power-law fosters more stress relaxation when coupled with primary creep, D decreases!
- Diffusion accounted for: no such tendency, API 579-1 damage up to 169%!

COMPARISON WITH THE OMEGA METHOD



- API 579-1 Omega method implemented in ANSYS via custom user sub-routine
- Results validated against published data (Vivio et al., 2013)
- Less conservative than LMP in every case!

$$D = \sum_i \frac{t_i}{L_i}$$

$$L = \frac{1}{\Omega_m \cdot \dot{\varepsilon}_{c0}}$$

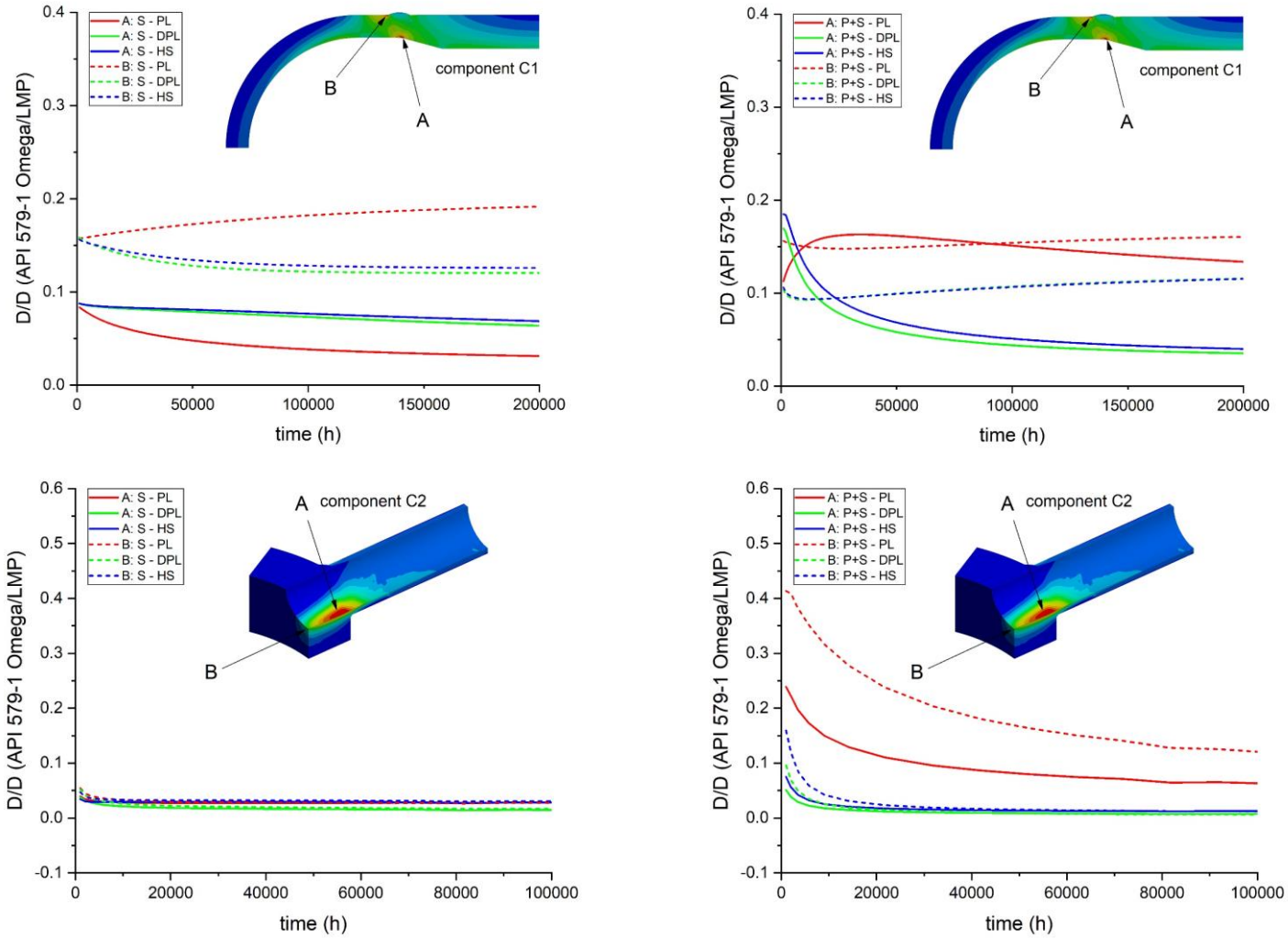
$$\dot{\varepsilon}_c(t) = \dot{\varepsilon}_{c0} \cdot e^{\Omega_m \varepsilon_c} = \frac{\dot{\varepsilon}_{c0}}{1 - \Omega_m \cdot \dot{\varepsilon}_{c0} t}$$

$$\Omega_m = \Omega_n^{\delta_\Omega + 1} + n_{BN}$$

$$\Omega_n = \max(\Omega - n_{BN}, 3.0)$$

$$\delta_\Omega = 0.33 \cdot \left(\frac{\sigma_1 + \sigma_2 + \sigma_3}{\sigma_{VM}} - 1.0 \right)$$

COMPARISON WITH THE OMEGA METHOD



CONCLUSIONS

- Creep damage assessment crucial for FFS of pressure equipment at high temperatures

- Three stages of creep: primary, secondary and tertiary, two microstructural processes: dislocation sliding and diffusion

- First step of research: role of diffusion and assessment of 3 secondary creep formulations: Norton's power-law (PL, dislocation-controlled), double power-law and Garofolo's hyperbolic sine (DPL and HS, diffusion/dislocation-controlled)

- Norton's power-law conservative in terms of API 579-1 residual life <u>only at points of stress concentrations</u> (lower relaxation rates)

CONCLUSIONS

- In this work: analysis extended **including primary creep modeling**
- API 579-1/LMP creep damage via FEA + custom creep models (PL, DPL, HS – secondary creep, primary+secondary creep)
- Primary creep increased API 579-1/LMP damage in every case except for PL at stress concentrations
- Common assumption of negligible primary creep not confirmed, especially with diffusion
- API 579-1/Omega creep damage (FEA + custom user sub-routine): way less conservative than LMP (< 20% ratio, secondary creep - < 40% ratio, primary+secondary creep)

CONCLUSIONS

THANK YOU!