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A multi-mechanism model for fast characterization of high cycle fatigue of alloys in the presence of process-induced pores

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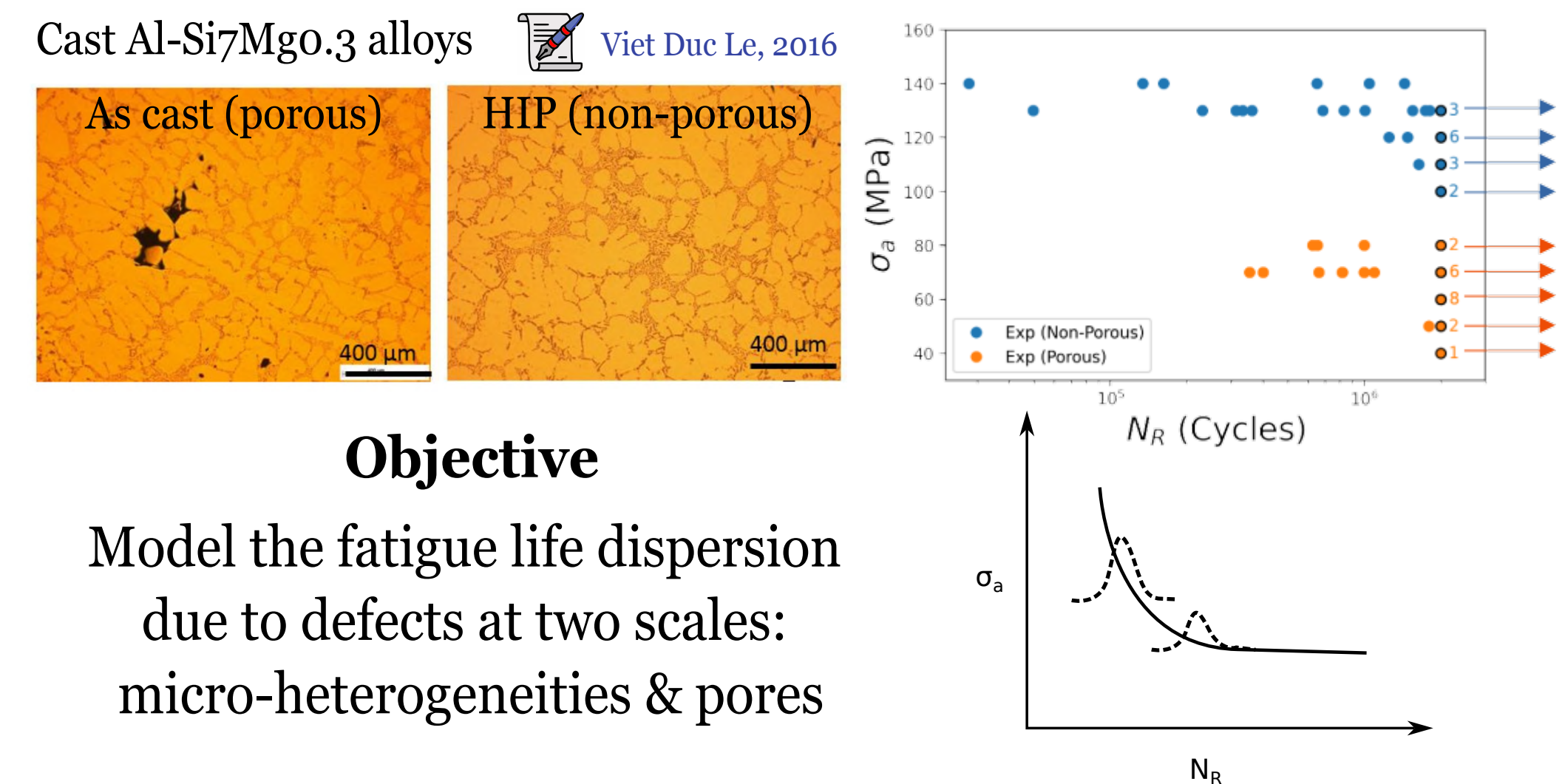
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HIGHLIGHTS

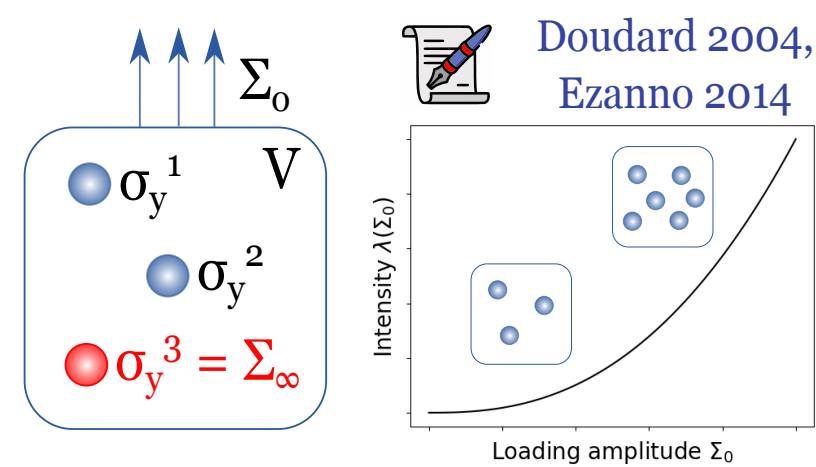
- A micro-mechanical model is modified via a weakest link hypothesis to model HCF lifetime uncertainty in heterogenous specimens, with the parameters being identified via a maximum likelihood estimate.
- The proposed multi-mechanism model takes into account uncertainty at two scales: micro-defects and meso-scale pores of complex morphology, and is capable of taking into account the size effect.
- Some pores show high stress concentration factors that cause plasticity even in the high-cycle fatigue regime, which is taken into account via accelerated full-field Neuber-type plasticity calculations for proportional loadings. The identified model is capable of fast prediction of fatigue life for porous or non-porous structures, with or without plasticification.

CONTEXT



MICRO-INCLUSION MODEL

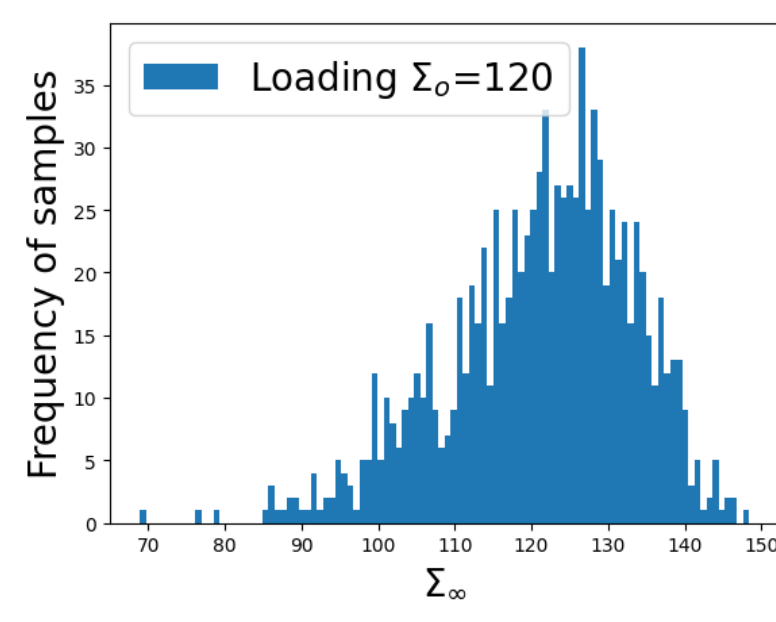
Assumptions: Micro-plastic inclusions appear according to a Poisson process in a volume V (with intensity as a power law of the loading Σ_o)



Yield of the weakest inclusion is defined as Σ_∞ and the distribution for its appearance becomes a 2-parameter Weibull due to the assumptions

$$\Sigma_\infty = \min_{sites} \sigma_y^{sites} \quad \lambda = S_o \left(\frac{V_o}{V} \right)^{1/m}$$

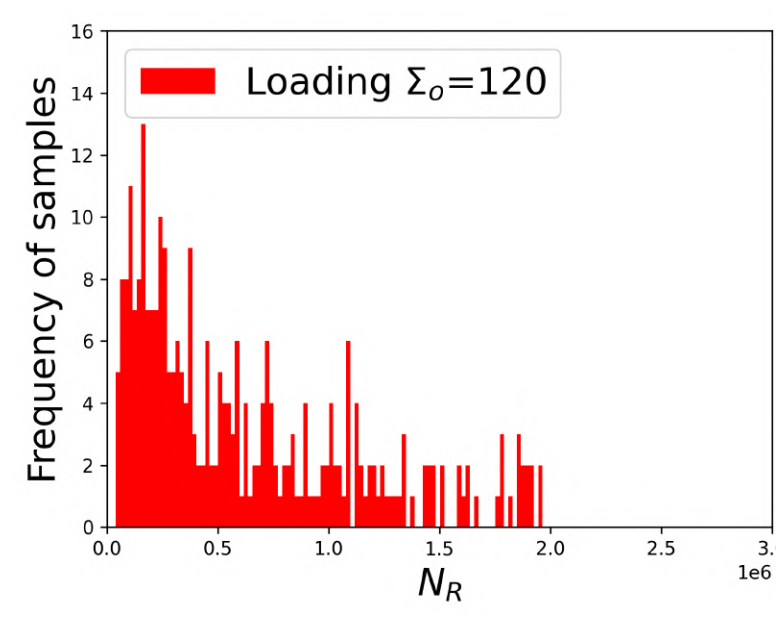
$$f_{\Sigma_\infty}(\Sigma_o) = \frac{m}{\lambda} \left(\frac{\Sigma_o}{\lambda} \right)^{m-1} \exp \left(- \left(\frac{\Sigma_o}{\lambda} \right)^m \right)$$



Fatigue life (N_R) is derived via a critical value of cumulated plasticity of the weakest inclusion (Σ_∞). The stochasticity of Σ_∞ makes N_R a probability distribution.

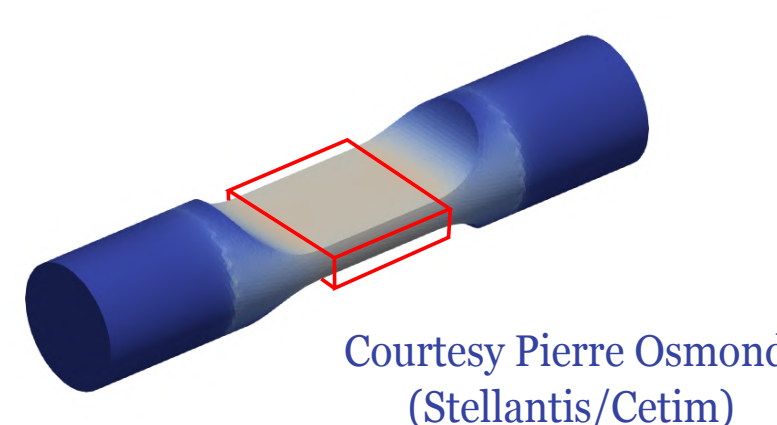
$$N_R = \begin{cases} \frac{A}{(\Sigma_o - \Sigma_\infty)^2}, & \text{if } \Sigma_o < \Sigma_\infty \\ +\infty, & \text{if } \Sigma_o \geq \Sigma_\infty \end{cases}$$

$$f_{N_R}(N) = f_{\Sigma_\infty}(\Sigma_o) \left| \frac{d\Sigma_o}{dN} \right|$$



EXTENSION TO HETEROGENOUS STRESSES

Tomography of planar specimens



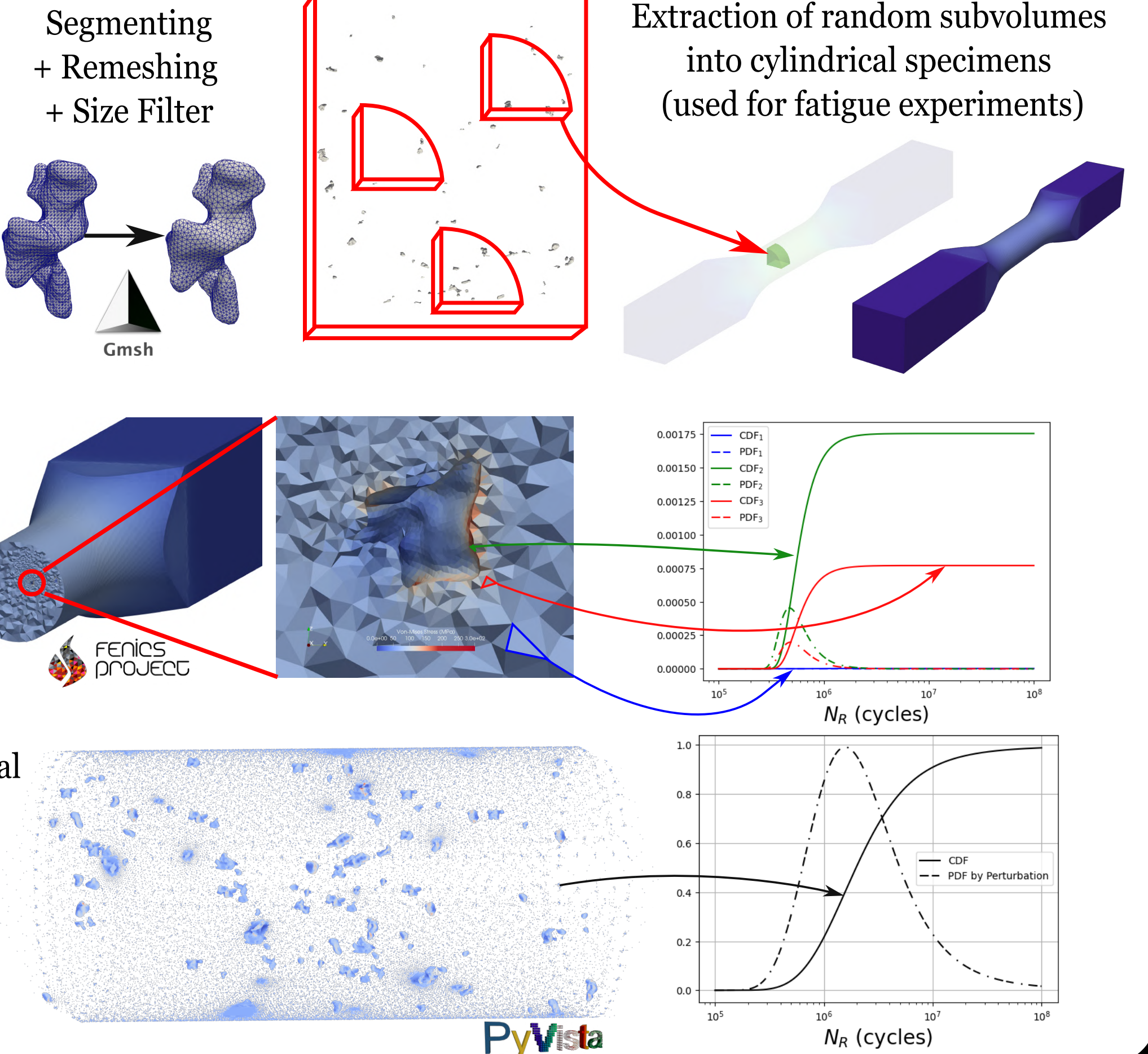
Probability of structure surviving is governed by the probability of its constituent elements surviving

$$Prob(N_R^s > N) = \prod_e Prob(N_R^e > N)$$

$$1 - F_{N_R}^s(N) = \prod_e (1 - F_{N_R}^e(N))$$

The parameters $\mu = [m, S_o, A]$ are found over n experimental points over m levels of applied stress amplitudes via **Maximum Likelihood Estimation**

$$\mu = \arg \max_{\tilde{\mu}} \left(\sum_{i=1}^m \sum_{j=1}^n \ln f_{N_R}^s(N^{(i,j)}; \tilde{\mu}, \Sigma_o^i, V) \right)$$



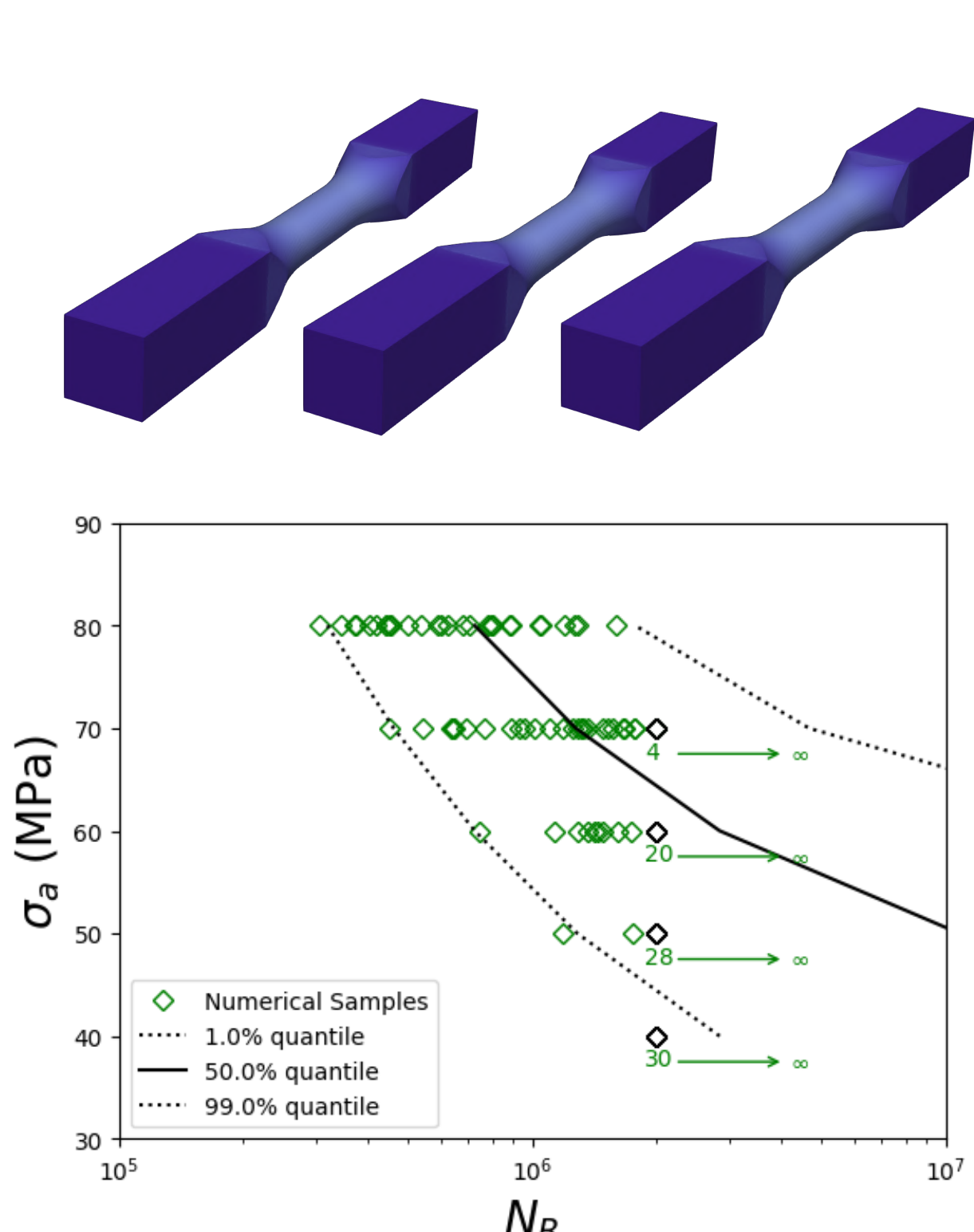
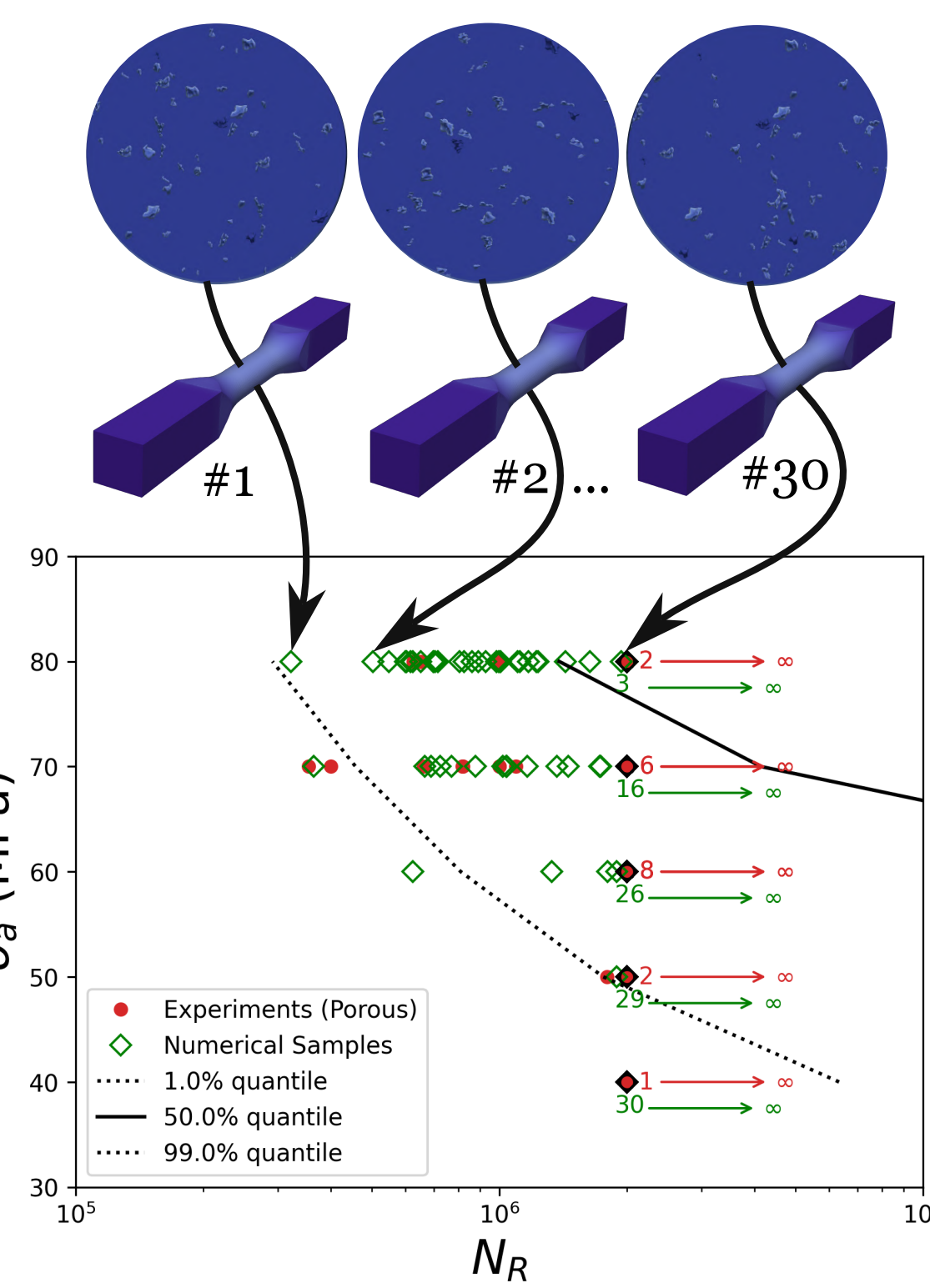
RESULTS - MODELLING INFLUENCE OF PORES

Uncertainty of two processes modelled:

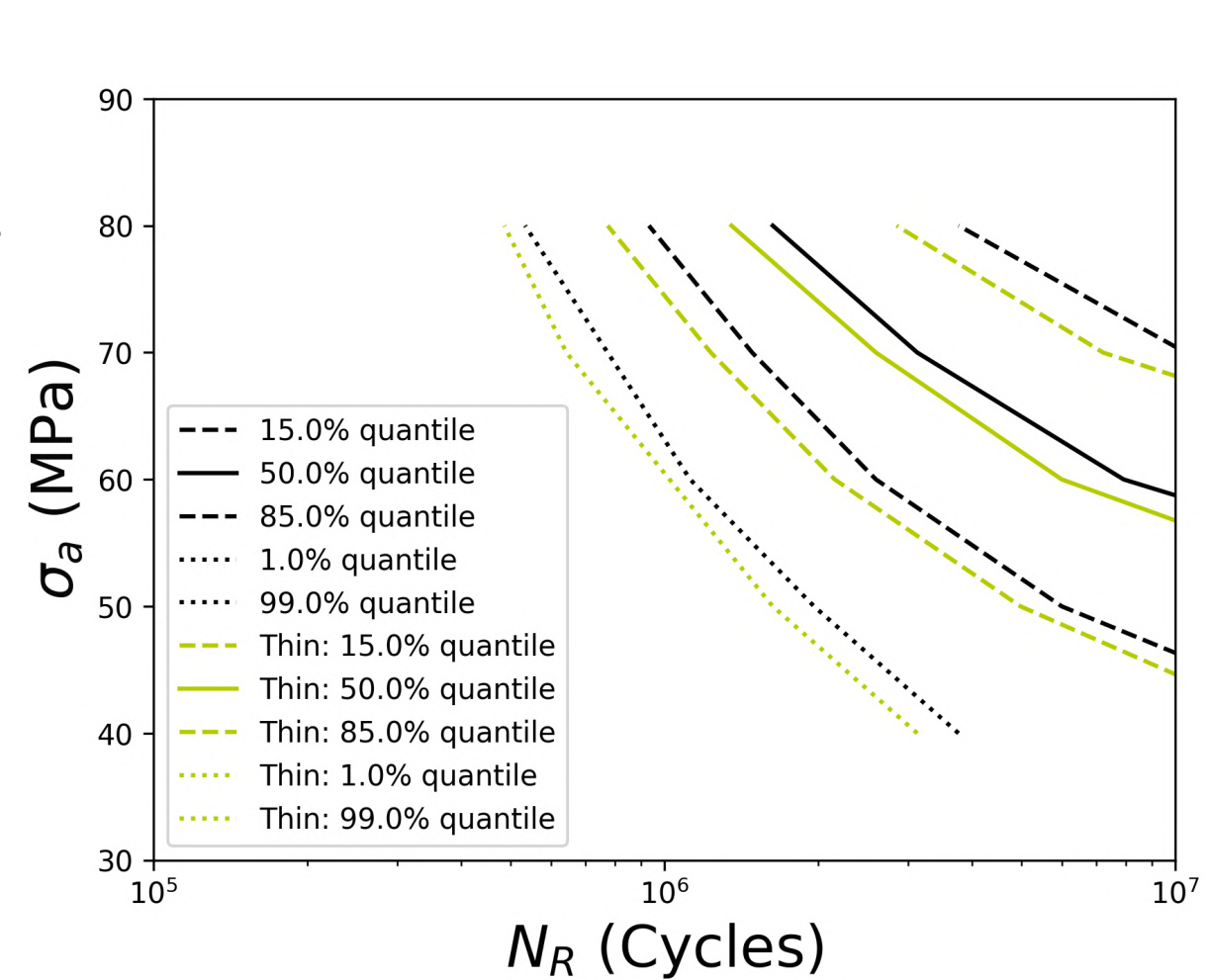
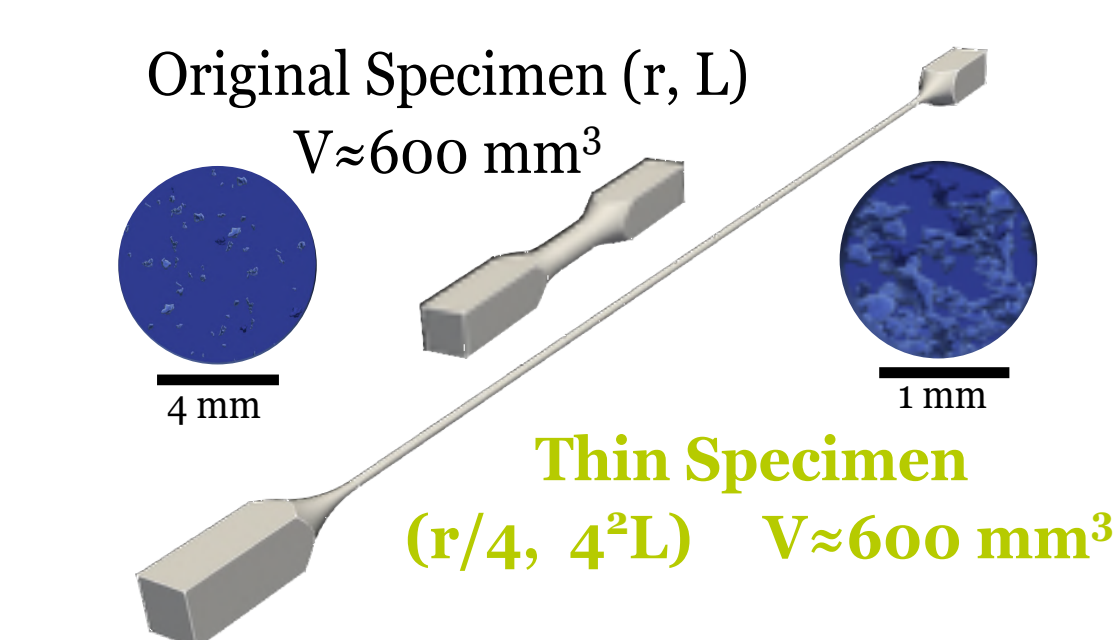
1. Micro-defects, via the micro-inclusion model
2. Meso-pores, as the distribution of pores is changed with every sample

Size effect modelled:

Bigger specimens have more chance of critical defects, and a lower fatigue life



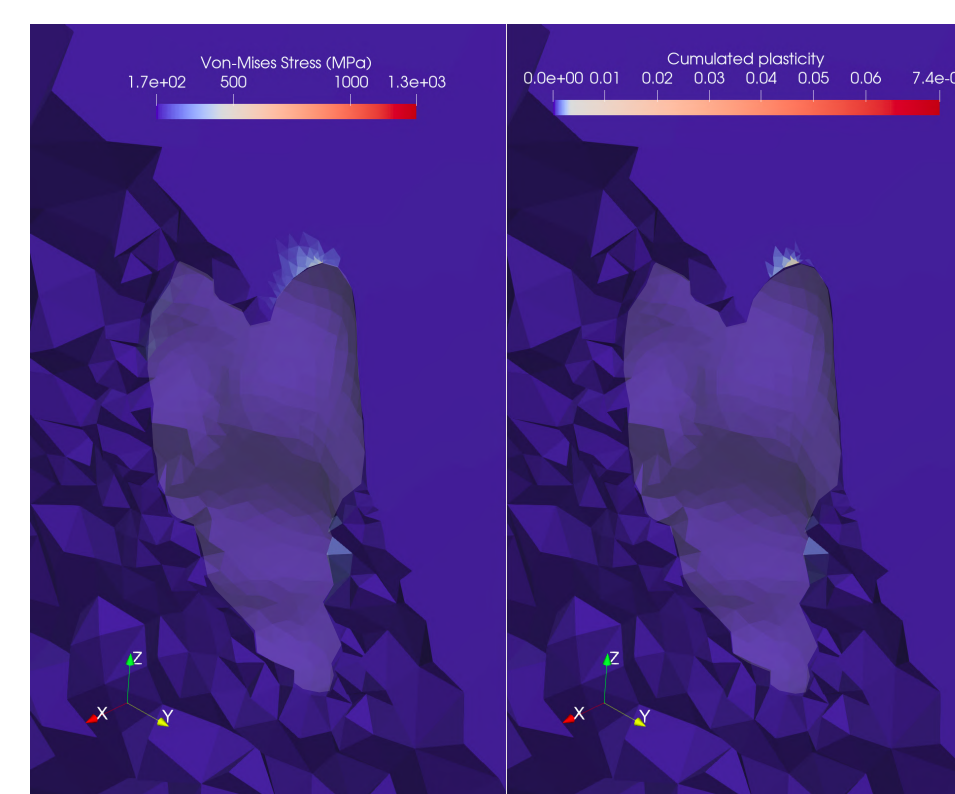
Size effect modelled:
For specimens of same volume: Thinner specimens have more pore-surface interaction, severe stress gradients & a lower fatigue life



**Plasticity due to pores:
Need for a second mechanism**

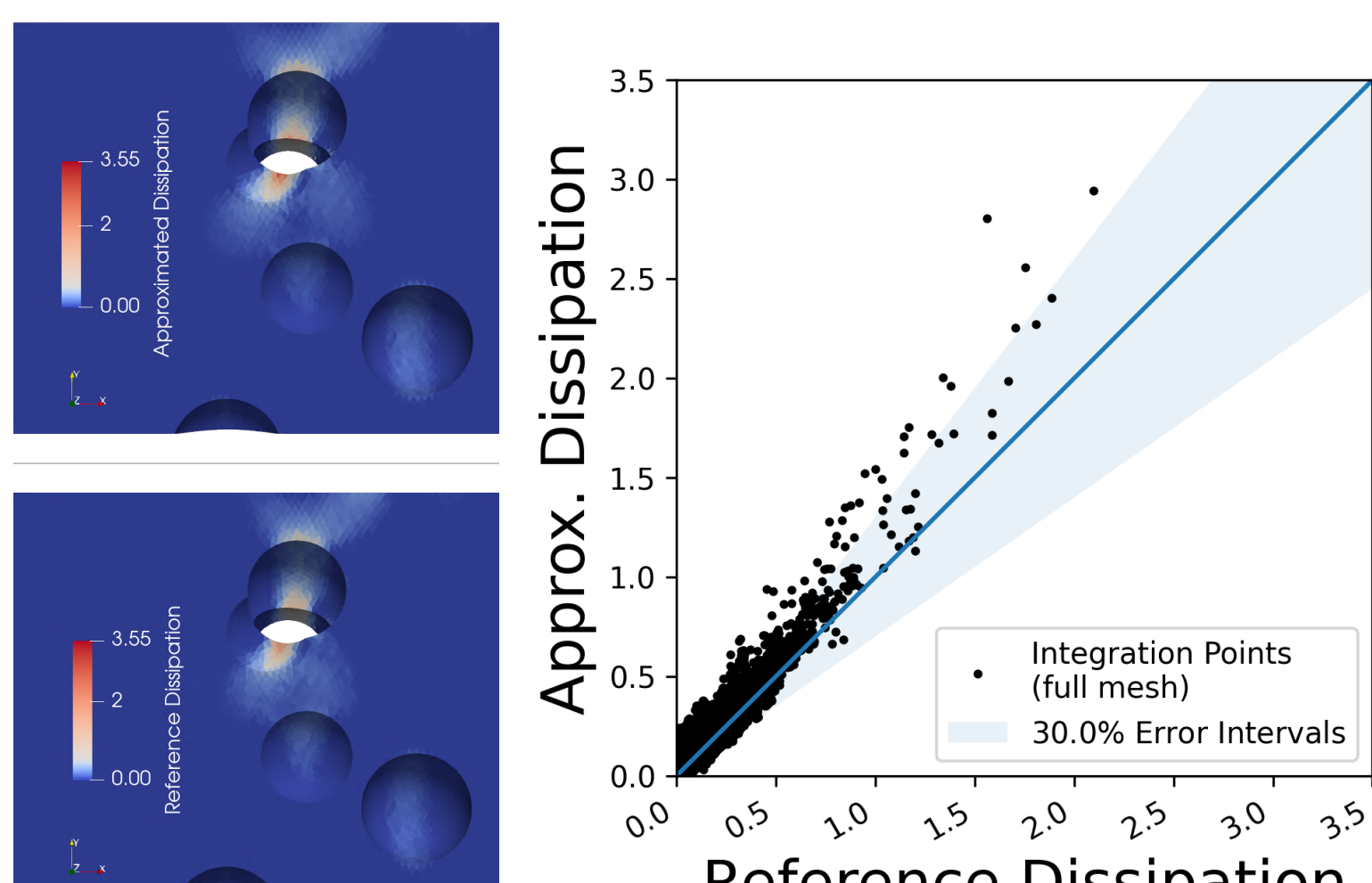
The micro-inclusion model is not applicable when the local loading is higher than σ_y , as there exist plastified zones which needs analysis on a separate scale.

Yield $\sigma_y = 170$ MPa
Stress concentration factors can be as high as 6 to 7 due to pores



Accelerated plasticity calculations

Module based on reduced Neuber-type rules adapted to fatigue loading [Palchoudhary et al. 2022], with a Gaussian Process for full-field plasticity approximations in a cycle. Elasto-plastic FE calculations can take days, proposed method takes minutes (cost of an elastic calculation)



**Multi-mechanism model
for porous and non-porous specimens**

Macro-fatigue life (N_{R2}), governed by cumulated plasticity in a stabilized cycle calculated via identified Chaboche law

$$N_{R2} = \frac{1}{(\Delta p)^6} [B \exp(C \Sigma_\infty) + D]$$

A transition between the two plasticity mechanisms is implemented at the local, element level.

$$F_{N_R}^e(N) = [1 - \alpha] F_{N_{R1}}^e(N) + \alpha F_{N_{R2}}^e(N)$$

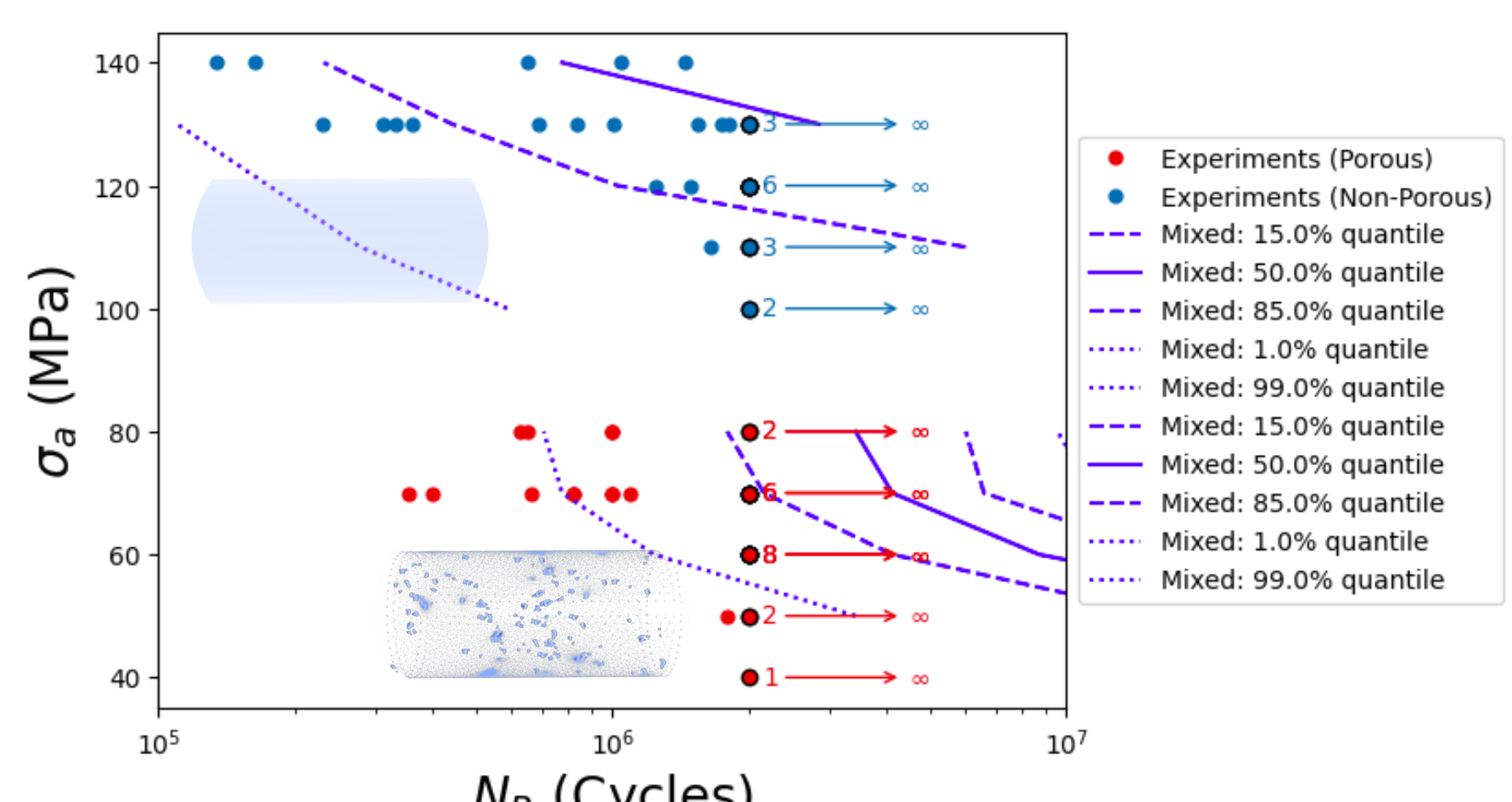
Micro **Macro**

$$\alpha(\Sigma_o) = \begin{cases} 0, & \text{if } \Sigma_o \ll \sigma_y \\ 1, & \text{if } \Sigma_o \gg \sigma_y \end{cases}$$

Weakest link over all elements for fatigue life

$$1 - F_{N_R}^s(N) = \prod_e (1 - F_{N_R}^e(N))$$

The parameters $\mu_1 = [m, S_o, A]$ are found with non-porous specimens, $\mu_2 = [b, B, C, D, \alpha]$ are found with porous specimens
Coherent predictions obtained for both types of specimens



FURTHER READING

Palchoudhary, A. Maurel, V. Ovalle-Rodas, C. Kerfriden, P. 2022. A fast Neuber-type finite element simulator to enable deep-learning-based fatigue life predictions from thermographic data. Congrès Français de Mécanique, Nantes, 2022.

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