Fatigue Test Modeling For The European INCEFA-SCALE Project

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1

Introduction and contextualization

The nuclear industry

- **The nuclear sector is crucial in the global energy landscape**
  - As of 2021, 69% of France's total generation comes from nuclear plants
  - Considered a clean energy source
- **Problem of aging**
  - Average nuclear reactor age worldwide: 31.9 years
  - In Europe, the average is of 35.6 years
- **Susceptibility to failure due to Fatigue**

INCEFA-SCALE project

- **Counts with multiple academical and industrial partners**
  - Framatome, CEA, Kaunas University of Technology (KTU), …
- **Works on Environmentally Assisted Fatigue (EAF)**
- **Objectives:**
  - Fill the laboratory-to-scale knowledge gap
  - Improve the lifetime predictions of components in a Nuclear Power Plant (NPP)
  - Review international guidelines to enhance the reliability of NPP components, such as the NUREG/CR-6909 Revision 1 report, from the United States Nuclear Regulatory Comission (NRC)

Computational tools used

- **Numerical simulations conducted using Salome Meca**
  - Combination of Salome and code_aster
  - Open source software developed by EDF
  - Possible to integrate Python, C++, C or Fortran code.
- **Salome:**
  - Powerful tool for CAD modeling, meshing, pre-processing and post-processing
- **code_aster**
  - Finite elements solver with easy to implement syntax
  - Possible to study a broad range of physical phenomena

Objective of this work

- **Conduct numerical simulations so as to:**
  - Reproduce the experiments from INCEFA-SCALE partners on the SAE 316L stainless steel
  - Validate the use of code_aster to accurately describe the mechanical behavior of laboratory specimens
  - Compare Finite Elements Analysis (FEA) results with test results
- **Additionally, experiment with different Chaboche constitutive model parameter sets**

2

Theoretical foundations of fatigue assessment

Motivation

- **Industrialization**
  - Economy heavily based on mass production, driven by mechanized manufacturing
  - Machines and transports depending on axles and rotating pieces
  - Components subjected constantly to cyclic loads
- **Catastrophic failures**
  - Often lethal, caused by the fatigue phenomenon
  - Affects different sectors, such as aeronautical, mining and railway

Motivation

Lithograph of the Versailles-Paris railway accident in may 8, 1842. Courtesy of the Bibliothèque Nationale de France

Failure due to cyclic pressurization in the de Havilland Comet I aircraft, the first commercial jet airliner, in 1954. Courtesy of the Royal Air Force (RAF) museum

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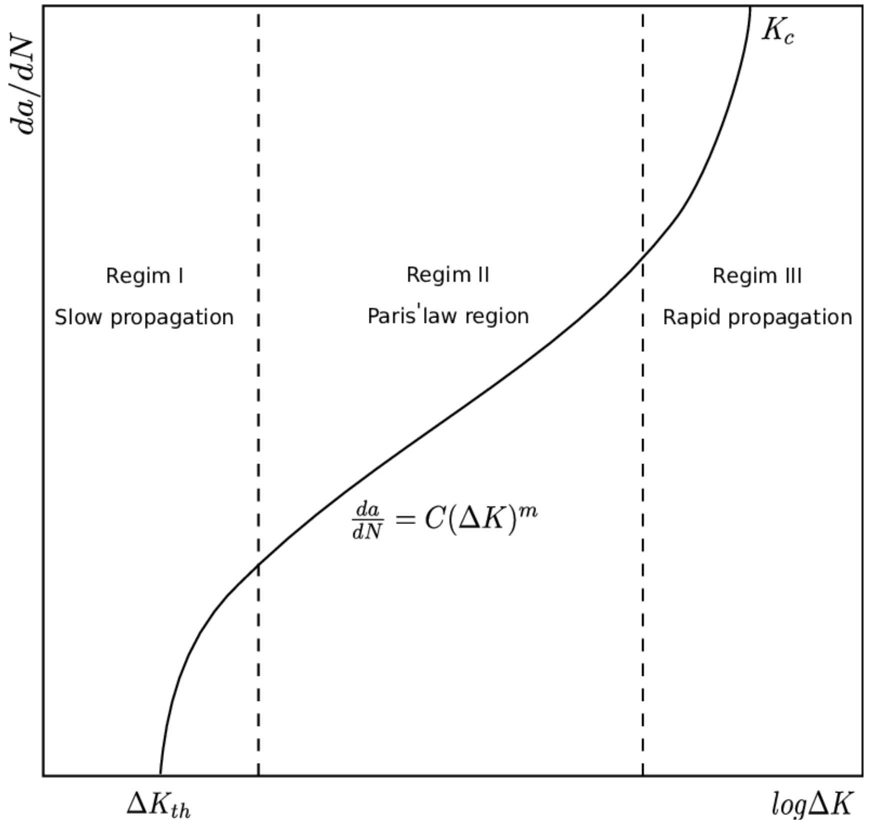
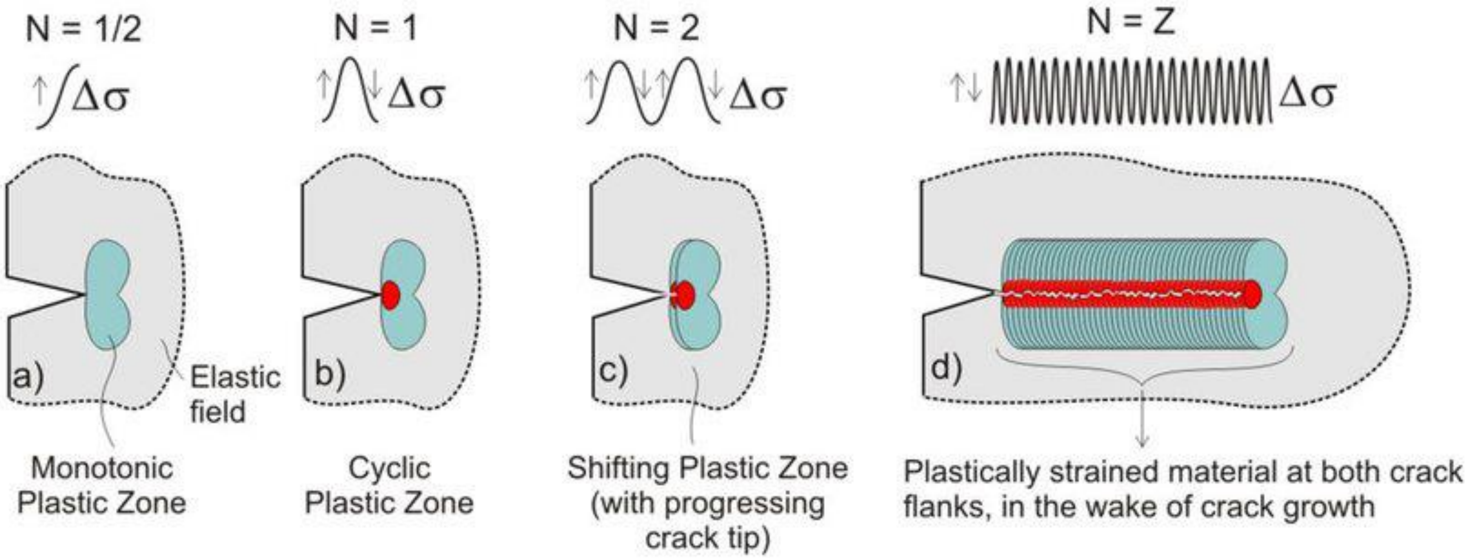
Fatigue

- Phenomenon where cyclic loads with $\sigma < \sigma_Y$ lead to rupture of a material
  - Surface imperfections
  - Stress concentration K
  - Vacancies
- Cumulative damage promotes crack growth throughout material's lifetime
- Paris law used to predict the rate of fatigue frack growth

$$\frac{da}{dN} = C(\Delta K)^m$$

Crack Growth





Ahmadivala, Morteza: Towards optimal maintenance planning of existing structures based on time-dependent reliability analysis. PhD thesis, December 2020.

Ghodrat, Sepideh, Ton Riemslag, and Leo AI Kestens: Measuring plasticity with orientation contrast microscopy in aluminium 6061-t4. Metals, 7(4):108, 2017.

Fatigue life stages

- Two fatigue life stages of interest for the INCEFA-SCALE project:
  - Maximum hardening stage
    - Early fatigue life
    - Material experiences cyclic hardening
  - Half life stage
    - Life stage where the number of cycles is half the necessary for rupture
    - Most real life machinery components are in this stage. Hence the importance of characterizing it accurately
    - Corresponding to stabilized cyclic behavior

3

The Chaboche Constitutive Model

Chaboche constitutive model

- All numerical simulations considered the Chaboche constitutive model
  - Designed as a way to characterize the **316L stainless steel**
  - Mathematical model with equations that account for the kinematic and the isotropic hardening effects
  - Particular focus on cyclic plasticity
  - Accounts for strain accumulation and recovering

Chaboche constitutive model

- code_aster is able to implement it easily
  - With history effect
    - Variable amplitude loading
  - Without history effect
- In the present work, we consider 2 kinematic hardenings
- One approach on parameter identification can be to solve an optimization problem

Strain partition	$\varepsilon = \varepsilon^e + \varepsilon^p$
Hooke's law	$\sigma = \frac{E\nu}{(1+\nu)(1-2\nu)} Tr(\varepsilon^e) I_d + \frac{E}{(1+\nu)} \varepsilon^e$
Field threshold	$f(\sigma, X, p) = J_2(\sigma - X) - (R(p) + R_0) \leq 0$ with $J_2(\sigma - X) = \sqrt{\frac{3}{2}(s - X) : (s - X)}$ and $s = \sigma - \frac{1}{3} Tr(\sigma) I_d$
Plastic flow	$\dot{\varepsilon}^p = \dot{\lambda} \frac{\partial f}{\partial \sigma} = \frac{3}{2} \dot{\lambda} \frac{s - X}{J_2(\sigma - X)}$ $f = 0$
Non-linear kinematic hardening	$X = \Sigma(X_i)$ $\dot{X}_i = \frac{2}{3} C_i(p) \dot{\varepsilon}^p - \gamma_i X_i \dot{p}$ with $C_i(p) = C_i^{\infty}(1 + (k - 1))e^{-wp}$ $\gamma_i(p) = \gamma_i^0(a_{\infty} + (1 - a_{\infty}))e^{-bp}$ and $\dot{p} = \sqrt{\frac{2}{3} \dot{\varepsilon}^p : \dot{\varepsilon}^p}$ where i represents each kinematic hardening component
Non-linear isotropic hardening	$\dot{R} = b(Q - R)\dot{p}$ $Q(q) = Q_0 + (Q_m - Q_0)(1 - e^{-2\mu q})$ $F = \frac{2}{3} J_2(\varepsilon^p - \xi) - q \leq 0$ $d\xi = \frac{1-\eta}{\eta} dq n^*$ n^* corresponds to the normal direction of surface F

Chaboche constitutive model

- **Important mechanical quantities**
  - In the whole study, we are going to rely in measures of two important mechanical quantities:
    - Von Mises equivalent stress σ_{VM}

$$\sigma_{VM} = \sqrt{\frac{3}{2} s_{ij} s_{ij}} = \sqrt{\frac{(\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{yy} - \sigma_{zz})^2 + (\sigma_{zz} - \sigma_{xx})^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)}{2}}$$

    - Von Mises equivalent strain ε_{VM}

$$\varepsilon_{VM} = \sqrt{\frac{2}{3} \mathrm{dev}(\varepsilon)_{ij} \mathrm{dev}(\varepsilon)_{ij}}$$

4

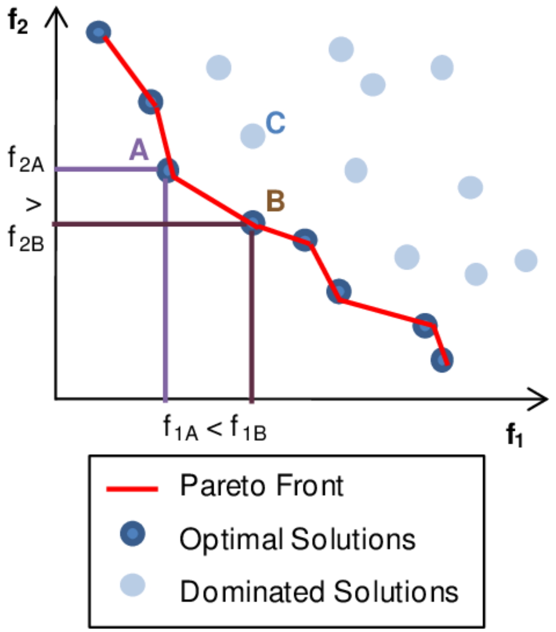
Multi-objective optimization and evolutionary algorithms

Basics of multi-objective optimization

- Optimization problems where two or more objectives are considered
- Objective: determine the Pareto front
  - Set of designs that dominates all others
- Typical mathematical formulation without constraints:

$$\text{minimize: } a_f = \{f_1(\mathrm{x}_a), f_2(\mathrm{x}_a), \dots f_m(\mathrm{x}_a)\}^T \in \boldsymbol{X} \subset \mathbb{R}^m$$
$$\text{by changing: } a \in \mathcal{X}$$

$$\mathbb{P}(\boldsymbol{X}) = \{a \in \mathcal{X} \mid \nexists b \in \mathcal{X},\ b_f \succ a_f\}$$

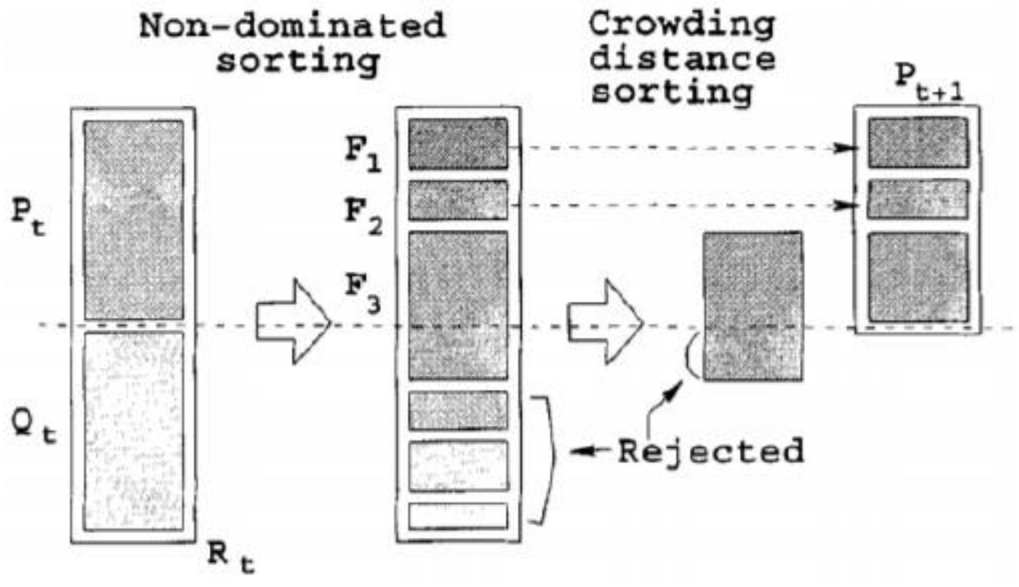


Evolutionary algorithms

- Based on principles of natural selection
  - Survival of the fittest
- Genetic information → DoE parameters
- Uses of crossover and mutation operators
- In this study, the NSGA-II algorithm is used
  - Crossover operator: Simulated Binary Crossover (SBX)
  - Mutation Operator: Polynomial Mutation
  - Individuals ranked according to their ranks and crowding distances d_i

$$\xi_{k,i} = \frac{f_{k,i+1} - f_{k,i-1}}{\max(f_k) - \min(f_k)} \longrightarrow d_i = \sum_{k=1}^{m} \xi_{k,i}$$

NSGA-II workflow and pseudocode



Algorithm 2 NSGA-II Procedure

$t \leftarrow 0$ {Set generation counting variable}
$n_{\text{gen}} \leftarrow K$ {Set total number of generations as K, for $K \in \mathbb{N}^*$}
while $t < n_{\text{gen}}$ **do**
  Compute Q_t from P_t {SBX and polynomial mutation}
  $R_t \leftarrow P_t \cup Q_t$ {Combine parent and offspring population}
  Compute $\mathcal{F} = (\mathcal{F}_1, \mathcal{F}_2, \ldots)$ {Algorithm 1}
  $P_{t+1} \leftarrow \emptyset$
  $i \leftarrow 1$
  while $|P_{t+1}| + |\mathcal{F}_i| \leq N$ **do**
    Sort $\mathcal{F}_i$ by crowding distance {Equation 15}
    $P_{t+1} \leftarrow P_{t+1} \cup \mathcal{F}_i$
    $i \leftarrow i + 1$
  end while
  Sort $\mathcal{F}_i$ by crowding distance {Equation 15}
  $P_{t+1} \leftarrow P_{t+1} \cup \mathcal{F}_i[1 : (N - |P_{t+1}|)]$ {Add the first $(N - |P_{t+1}|)$ elements of $\mathcal{F}_i$}
  $t \leftarrow t + 1$
end while

Deb, K., A. Pratap, S. Agarwal, and T. Meyarivan: A fast and elitist multiobjective genetic algorithm: Nsga-ii. IEEE Transactions on Evolutionary Computation, 6(2):182–197, 2002

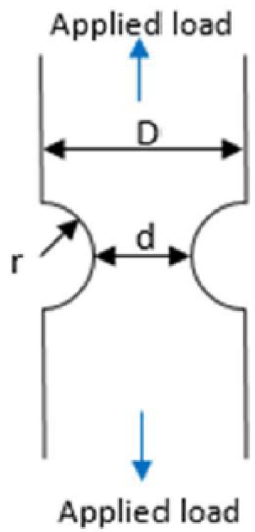
5

Results and discussion

- Part 1 – Validation of code_aster modeling
- Part 2 - Testing Chaboche parameter sets
- Part 3 – Optimization of parameters
- Part 4 – OPT parameters on specimens
- Part 5 – Variable amplitude loading

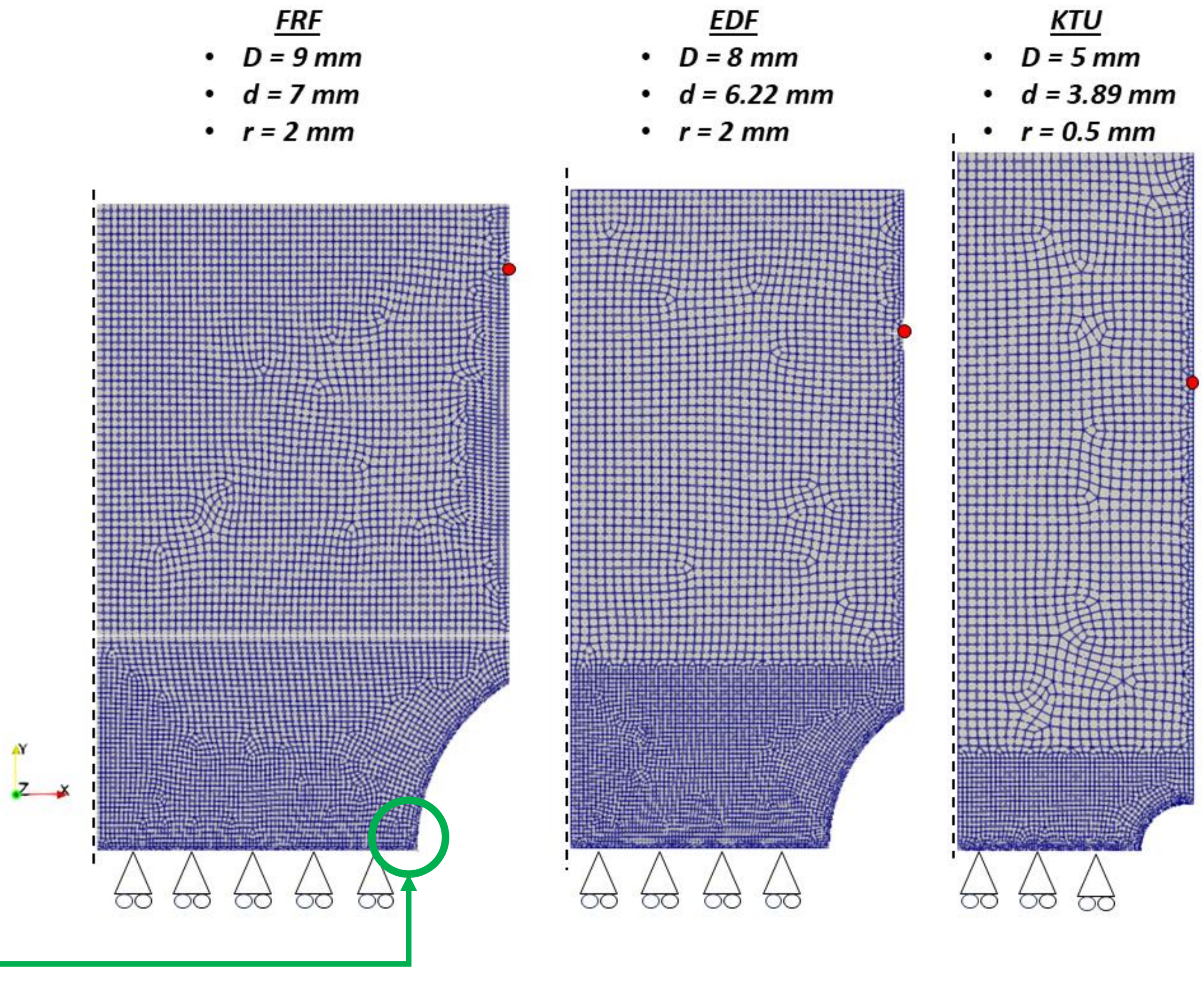
Notched specimen

- Study on the effects of geometry and load on notched specimens
- 3 geometrical parameters:
  - Nominal Diameter D
  - Reduced diameter d
  - Notch radius r
- Interest behind notched specimens:
  - Stress concentration region
  - Susceptible to crack generation
  - Common practice among experimental campaigns on fatigue
- All simulations considered T = 300°C



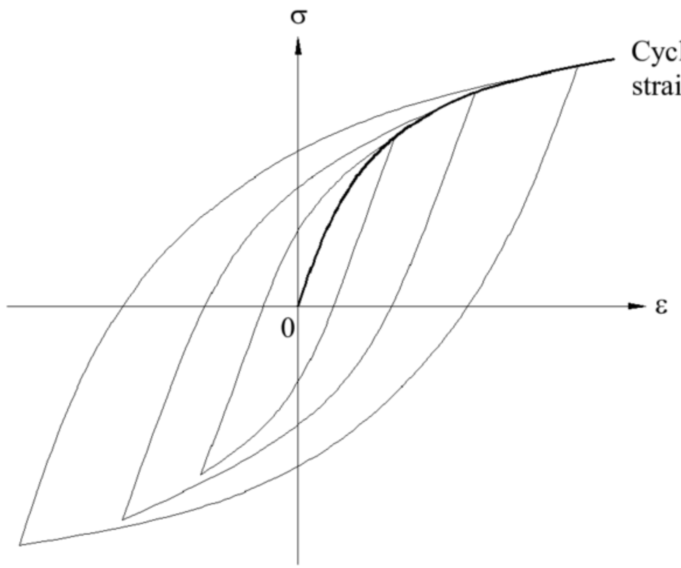
Part 1 – Validation of code_aster modeling

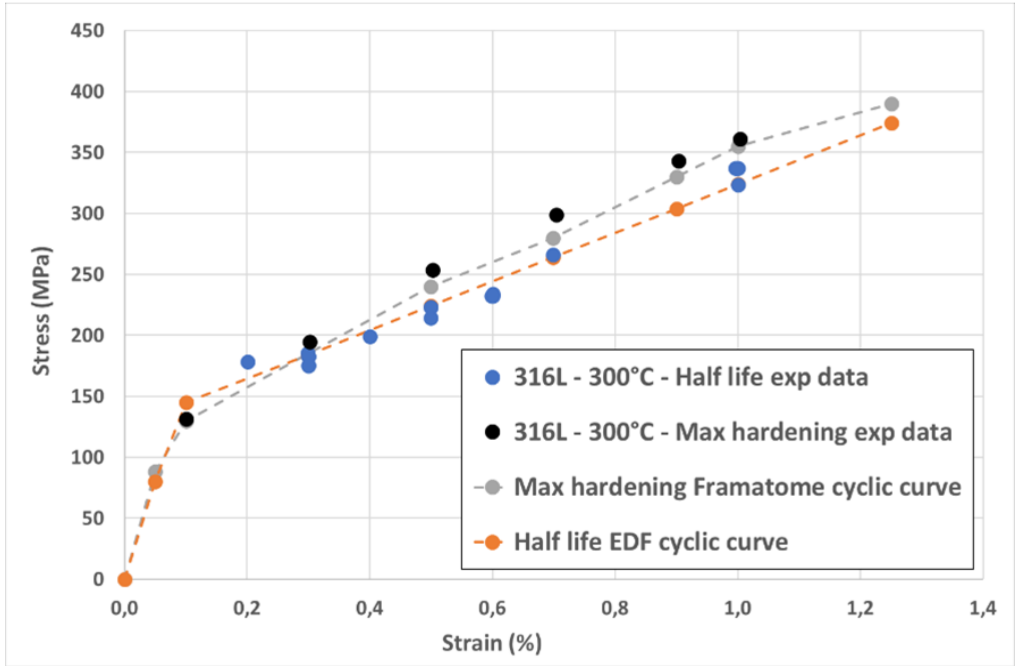
- Meshes used
  - Symmetry boundary conditions applied in order to use smaller domain and refine the mesh
- Red dot
  - Extensometer measurement



Part 1 – Validation of code_aster modeling

- Initial validation of code_aster framework using cyclic stress-strain curves on INCEFA-SCALE diagnostic tests

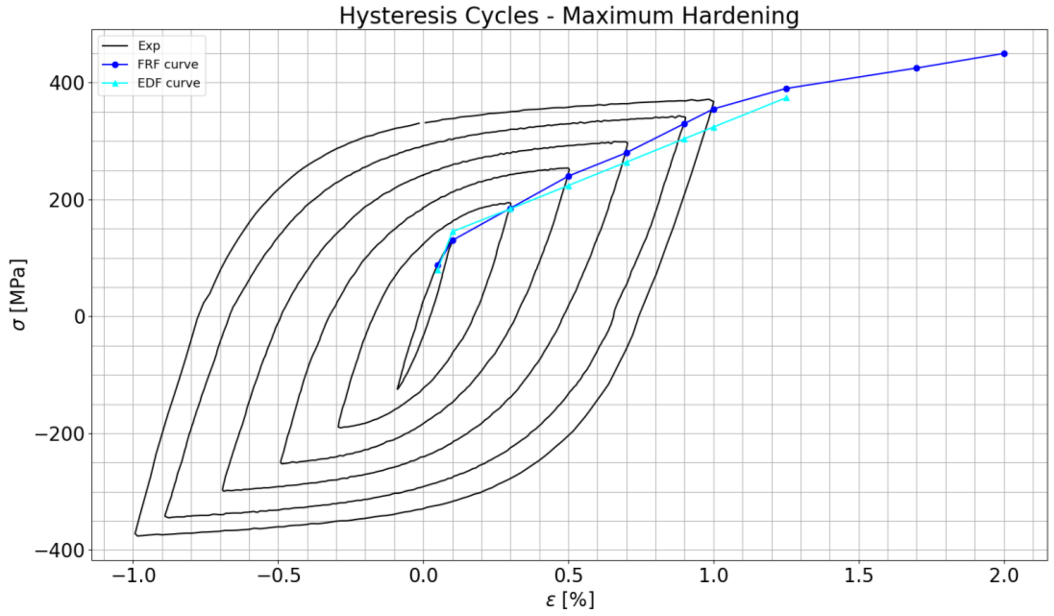


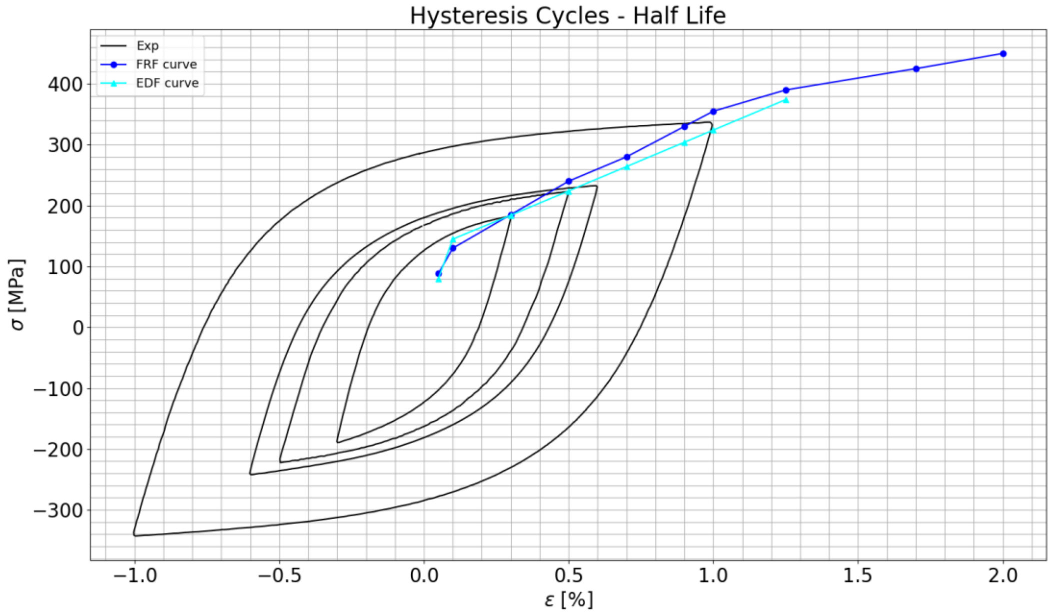


- Monotonic stress loading

Part 1 – Validation of code_aster modeling

- Comparison of used curves with available experimental data at maximum hardening and half life stages of fatigue life





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Part 1 – Validation of code_aster modeling

- Results (Notch, Extensometer)

Lab	Step	F[N]	Target ε_{VM}[%]	ε_{VM}[%]-FRF curve	ε_{VM}[%]-EDF curve	Ext. amplitude[mm]	FEA-FRF[51]	FEA-CEA[51]	FEA-FRF curve	FEA-EDF curve
FRF	-	8908	0.6000	0.6011	0.5956	0.0240	0.0257	0.0259	0.02553	0.02177
EDF	1	4737	0.2000	0.2003	0.1773	0.0080	0.0095	0.0112	0.00948	0.00926
	2	6108	0.4000	0.4006	0.3511	0.0126	0.0171	0.0171	0.01732	0.01436
	3	7147	0.6000	0.5995	0.6009	0.0238	0.0272	0.0220	0.02709	0.02356
KTU	1	1521	0.2000	0.2002	0.1961	0.0054	0.0051	0.0058	0.00501	0.00550
	2	2107	0.4000	0.4009	0.3446	0.0100	0.0089	0.0104	0.00891	0.00816
	3	2447	0.6000	0.6016	0.5440	0.0168	0.0125	0.0132	0.01255	0.01063

Lab	Step	δ_y[%]-FRF	δ_y[%]-CEA	δ_y[%]-FRF curve	δ_y[%]-EDF curve
FRF	-	7.08	7.92	6.38	-9.31
EDF	1	18.75	40.00	18.53	15.77
	2	35.71	35.71	37.47	13.96
	3	14.29	-7.56	13.82	-0.89
KTU	1	-5.56	7.41	-5.65	1.80
	2	-11.00	4.00	-10.87	-18.41
	3	-25.60	-21.43	-25.32	-36.71

$$\delta_y = \frac{\Delta y^{FEA} - \Delta y^{exp}}{\Delta y^{exp}}$$

Reference

Errors similar to FRF (reference)

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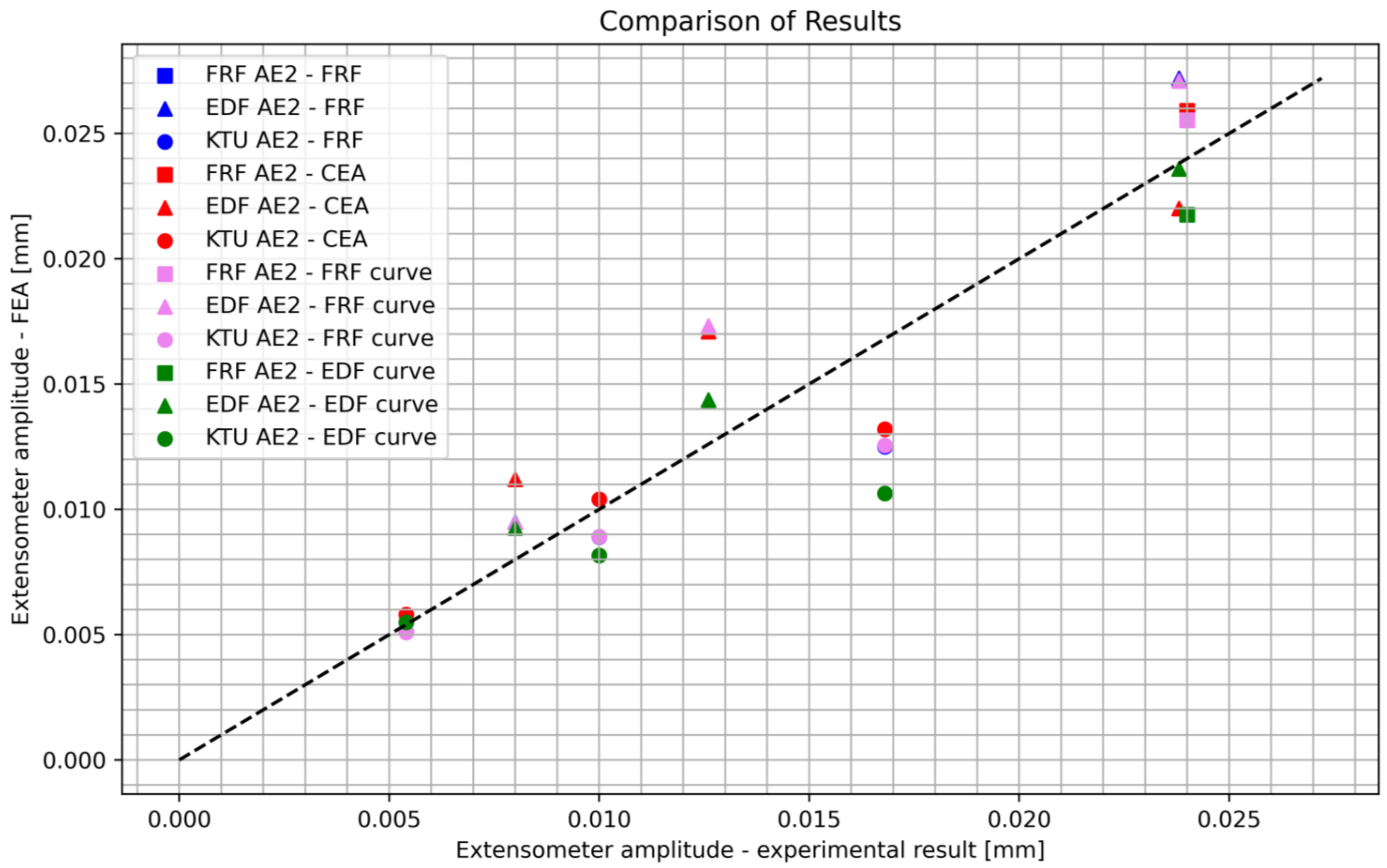
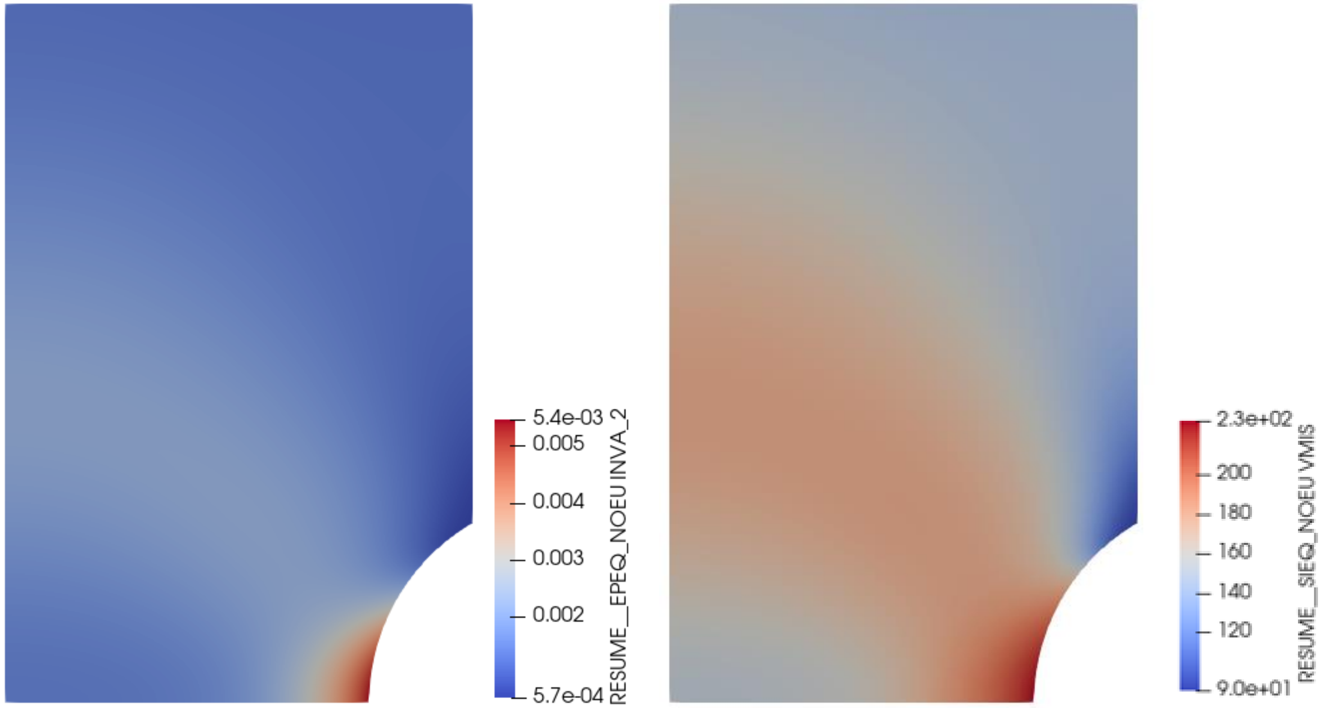
Part 1 – Validation of code_aster modeling

- Present code_aster modeling is considered to have been well implemented
- This gives credibility to further simulation results



Part 1 – Validation of code_aster modeling

- General strain and stress profiles (FRF specimen)



Part 2 – Testing Chaboche parameter sets

- Former strategy cannot be used for cyclic simulations
- Objective: test the parameter sets provided by CEA in the INCEFA-SCALE project and Zhang's parameter set*
- We seek to determine if any of these parameter sets is good enough to proceed with full-scale specimen simulations
- First approach:
  - Used simple cubic mesh to reduce computational burden

*Zhang, Wen: Fatigue crack growth in large scale yielding condition. PhD thesis, Université Paris Saclay (COmUE), 2016.

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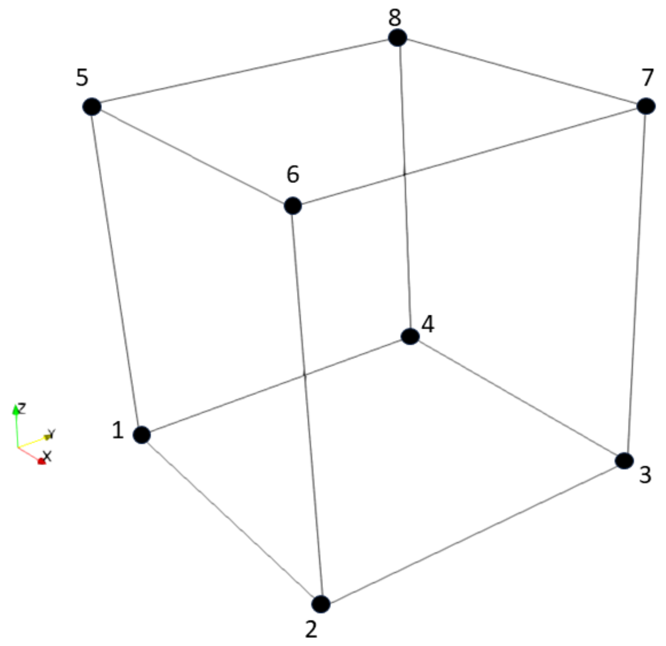
Part 2 – Testing Chaboche parameter sets

- **Mesh and boundary conditions:**
  - Nodes 1, 2, 3 and 4: no displacement in the z direction
  - Nodes 1, 2, 5 and 6: no displacement in the y direction
  - Nodes 1, 4, 5 and 8: no displacement in the x direction
  - Nodes 5, 6, 7 and 8: imposed displacement in the z direction



- **Strain controlled simulations**
  - Total of 100 cycles per strain amplitude $\Delta\varepsilon/2$
    - $\Delta\varepsilon/2 \in \{0.1, 0.3, 0.5, 0.6, 0.7, 0.9, 1.0\}\%$

Part 2 – Testing Chaboche parameter sets

- Parameter sets tested

	Parameters	Zhang	CEA-1	CEA-2	CEA-3	CEA-4
Elasticity	E [GPa]	160	160	160	160	180
	ν	0.3	0.3	0.3	0.3	0.3
Kinematic Hardening	C_1 [MPa]	170000	90000	136000	182000	87000
	γ_1	1500	1000	1200	1600	1000
	C_2 [MPa]	25000	34200	36400	32400	34100
	γ_2	200	214	303.194	303.194	212
Isotropic Hardening	R_0 [MPa]	110	800	5	55	5
	b	10	1	1	0.25	4

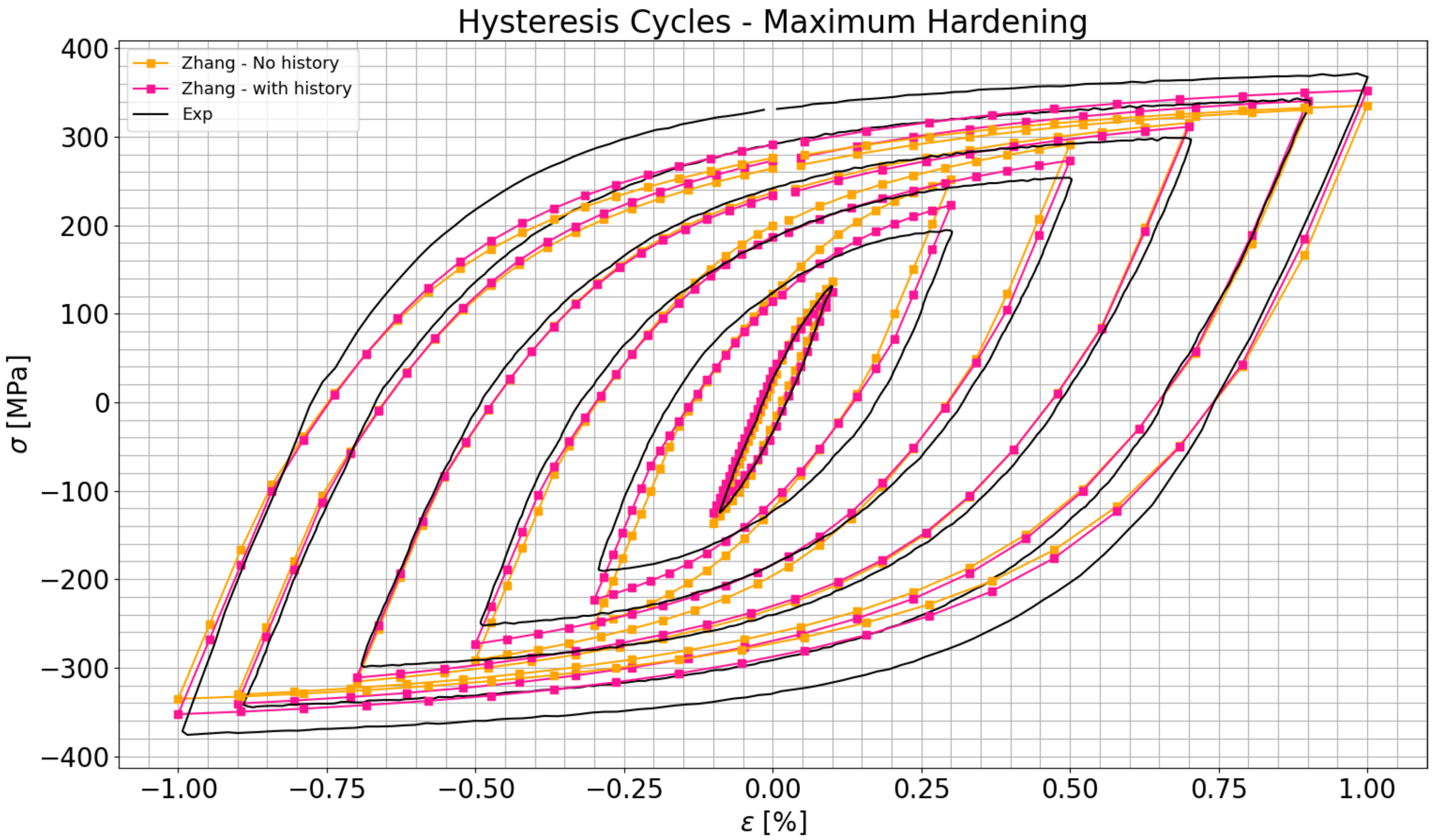
	Parameters	Zhang
History effect	μ	16
	η	1
	Q_0 [MPa]	-50
	Q_m [MPa]	250

With history effect

Part 2 – Testing Chaboche parameter sets

- Comparison of Zhang parameters (history effect)

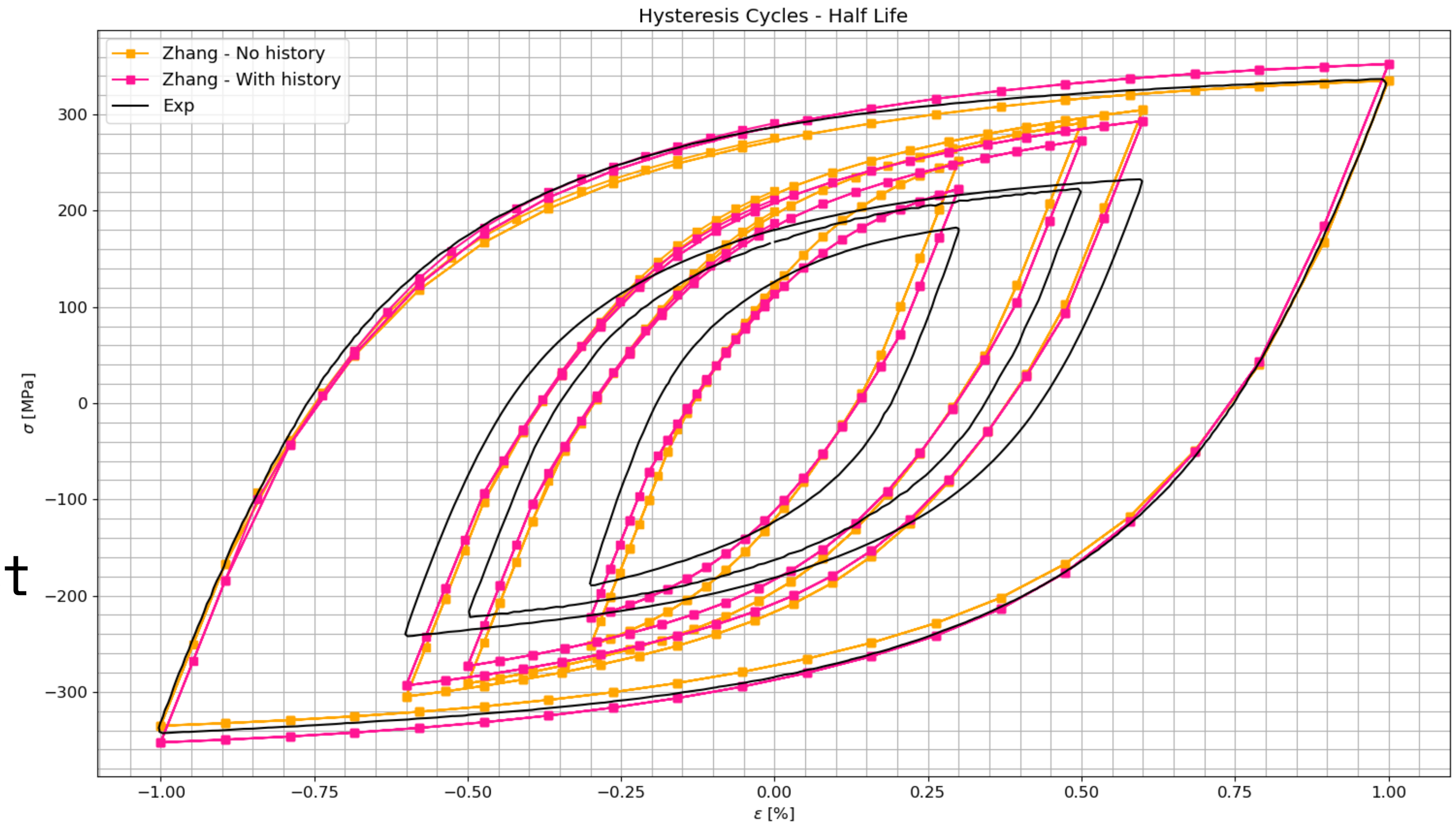
- **Best sets:**
  - Maximum hardening:
    - with history effect



Part 2 – Testing Chaboche parameter sets

- Comparison of Zhang parameters (history effect)

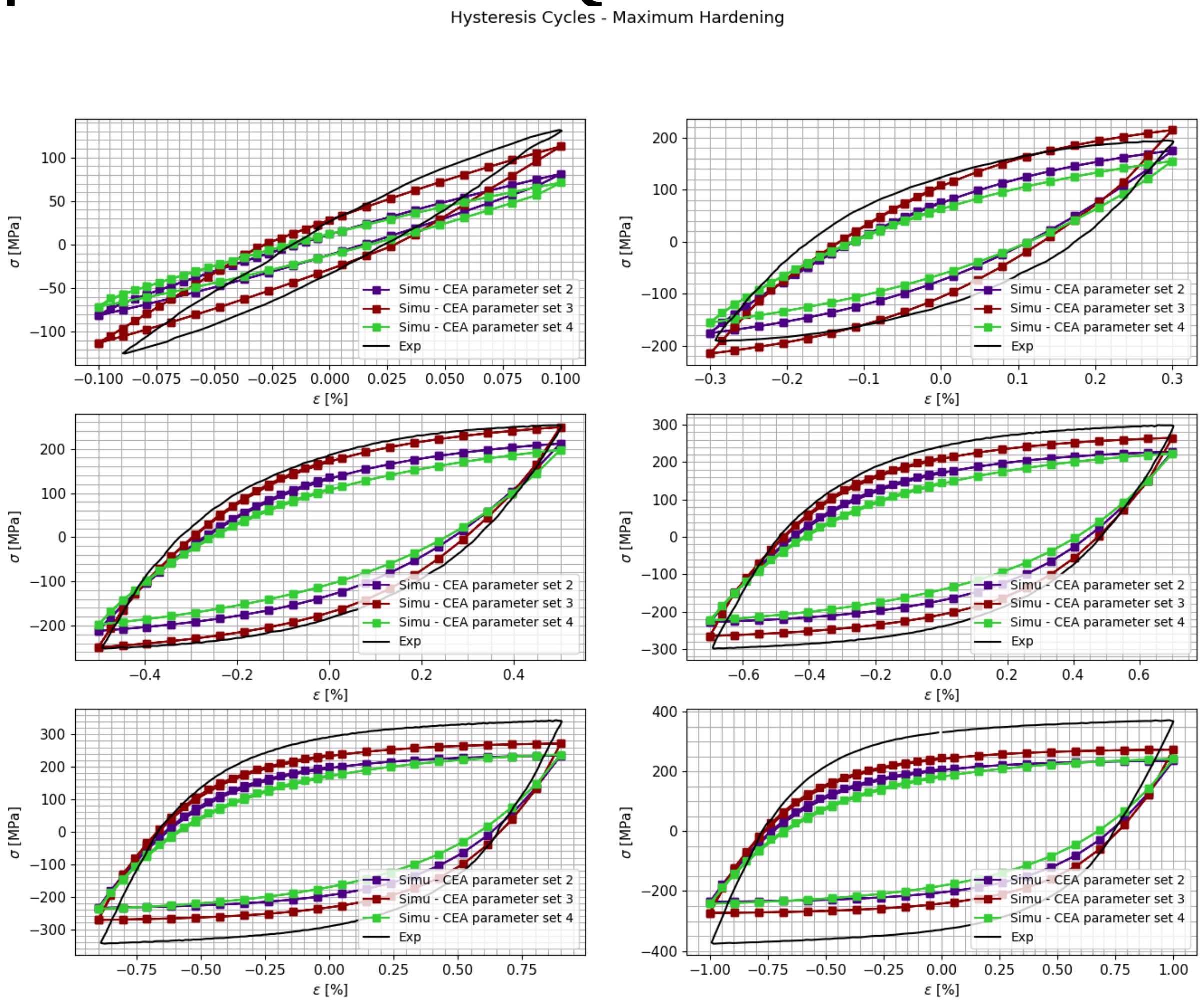
- **Best sets:**
  - Maximum hardening:
    - with history effect
  - Half life:
    - without history effect



Part 2 – Testing Chaboche parameter sets

- Comparison with CEA parameter sets (Parameter set 1 not considered)

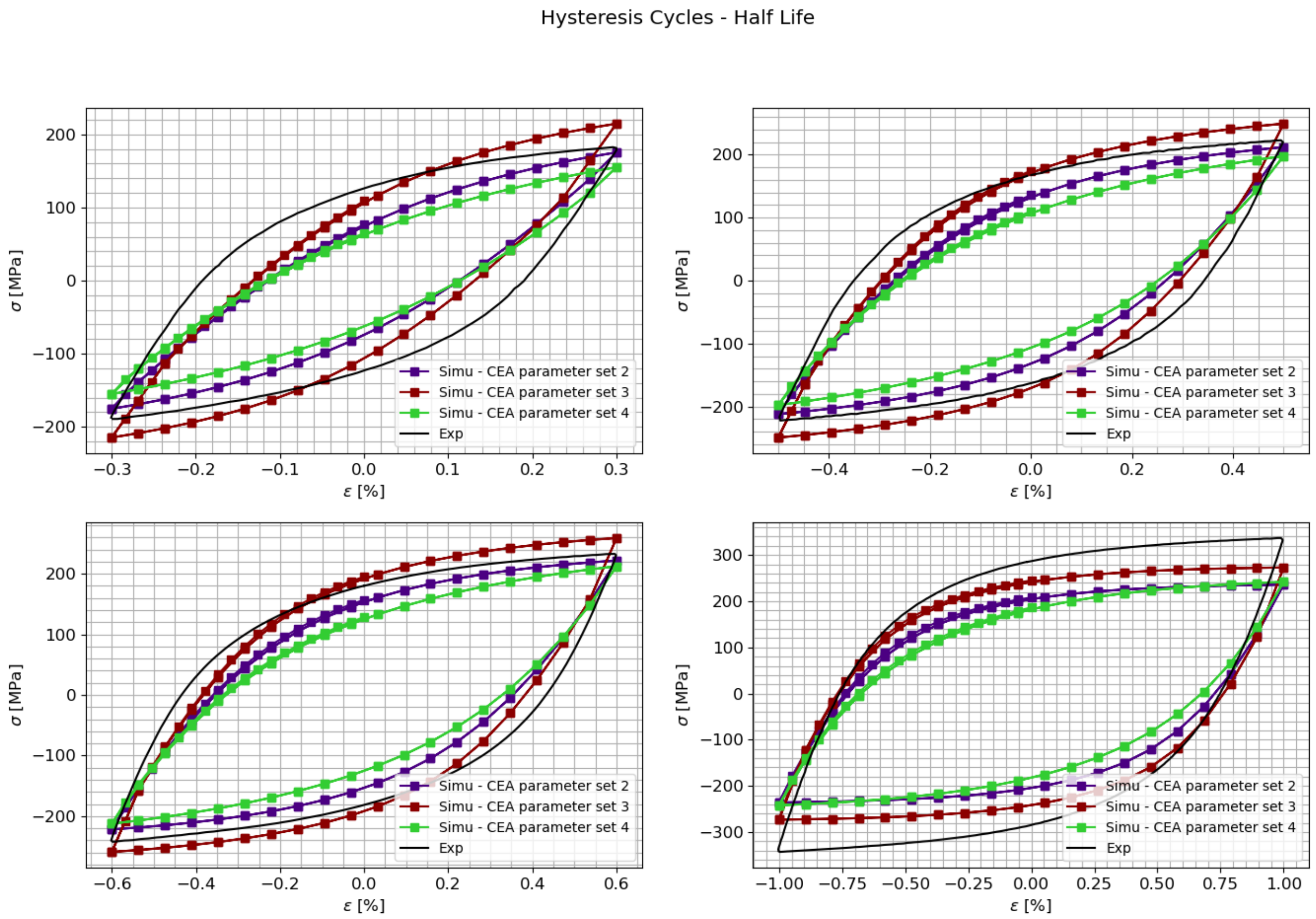
- Conclusion:
  - Maximum hardening: parameter set 3



Part 2 – Testing Chaboche parameter sets

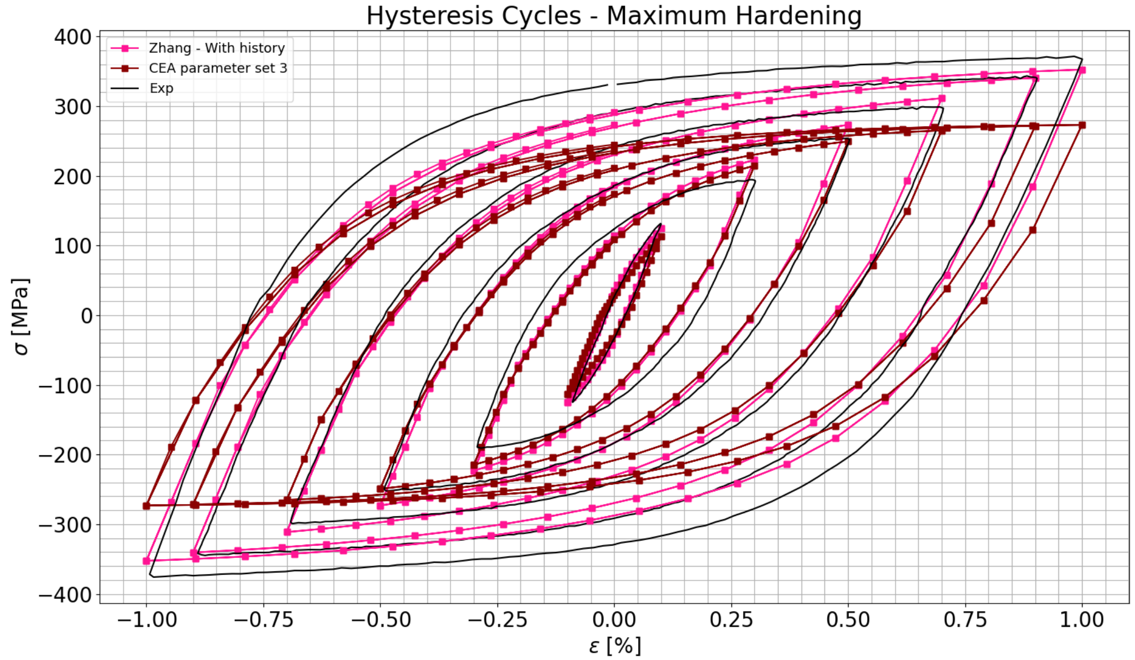
- Comparison with CEA parameter sets (Parameter set 1 not considered)

- Conclusion:
  - Maximum hardening: parameter set 3
  - Half life: parameter set 2



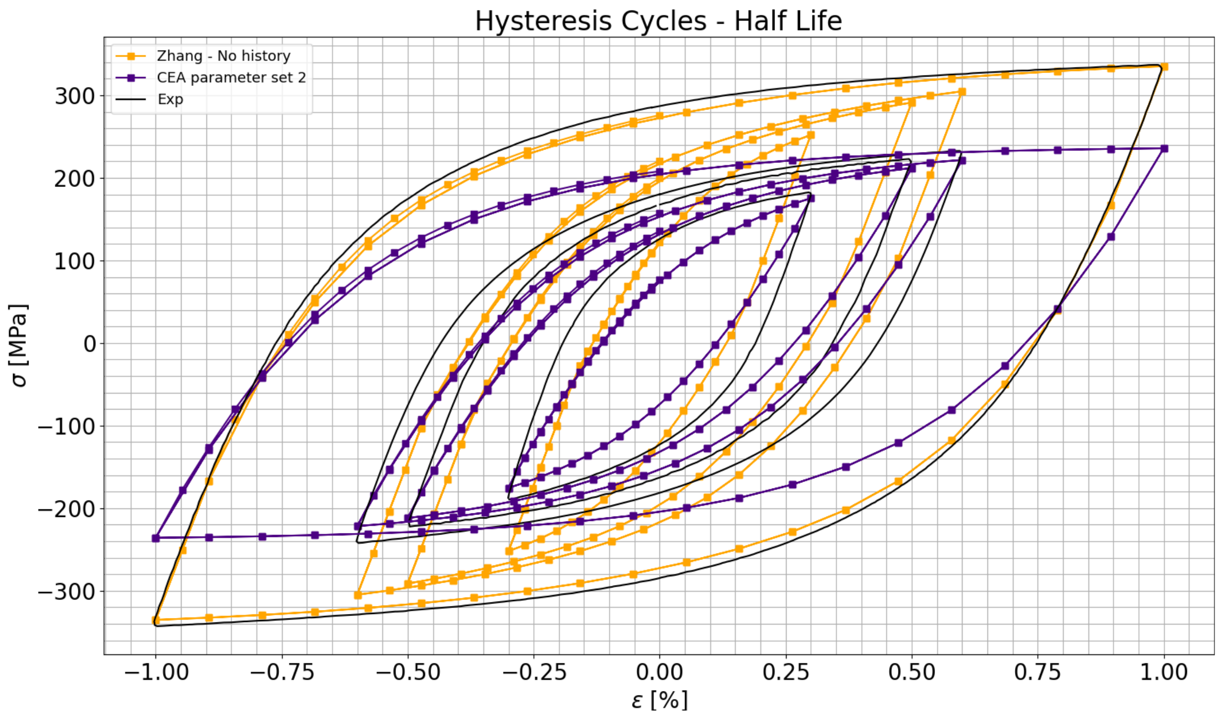
Part 2 – Testing Chaboche parameter sets

- Comparison of best parameter sets



Part 2 – Testing Chaboche parameter sets

- Comparison of best parameter sets

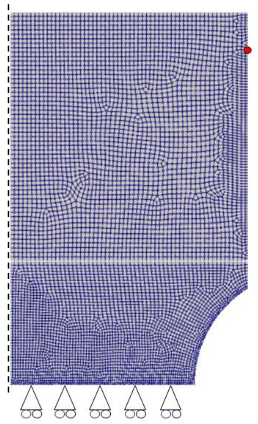


- CEA sets suitable for smaller strain ranges
- Zhang sets suitable for bigger strain ranges

Part 2 – Testing Chaboche parameter sets

- The rest of the work focuses only on analyzing the half life stage, for the interest of the INCEFA-SCALE project
- The best parameter sets (Zhang without history effect and CEA 2) were tested on FRF diagnostic specimen
  - Stress controlled simulation

Lab	Step	δ_y[%]-FRF	δ_y[%]-CEA	δ_y[%]-Zhang	δ_y[%]-CEA 2
FRF	-	7.08	7.92	-31.79	30.78



- Present FEA results are not good

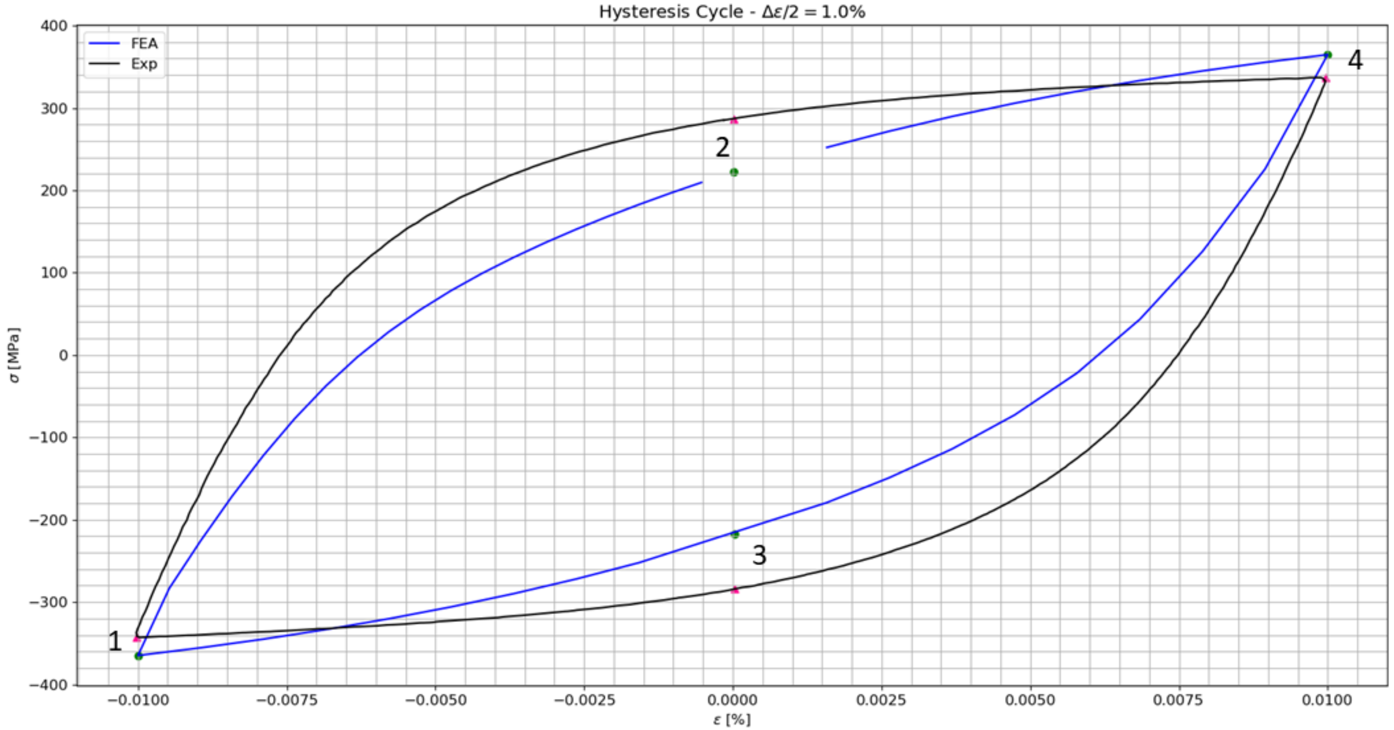
→ Optimization of these parameters is to be conducted

Part 3 – Optimization of parameters

- NSGA-II algorithm implemented considering:
  - Objective functions:

$$f_m = \sqrt{\sum_{i=1}^{4} \frac{(\sigma_{exp,i} - \sigma_{simu,i})^2}{4}}$$

  - DoE: $a = \{R_0, b, C_1, C_2, \gamma_1, \gamma_2\}^T$

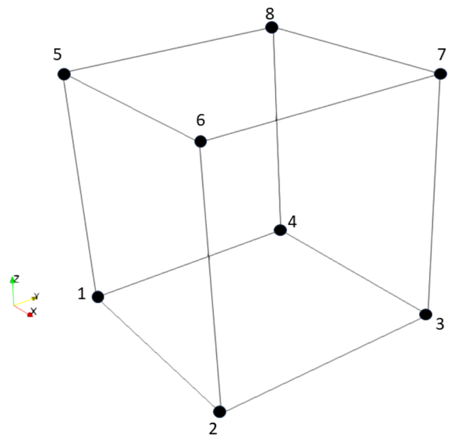


- Formulation:

$$\begin{aligned}
\text{minimize: } & a_f = \{f_1(\mathrm{x}_a), \ldots f_m(\mathrm{x}_a)\}^T \in \boldsymbol{X} \subset \mathbb{R}^m \\
\text{by changing: } & R_0 \in [50, 150] \text{ MPa} \\
& b \in [4, 12] \\
& C_1 \in [120000, 200000] \text{ MPa} \\
& C_2 \in [15000, 30000] \text{ MPa} \\
& \gamma_1 \in [1000, 2000] \\
& \gamma_2 \in [100, 300]
\end{aligned}$$

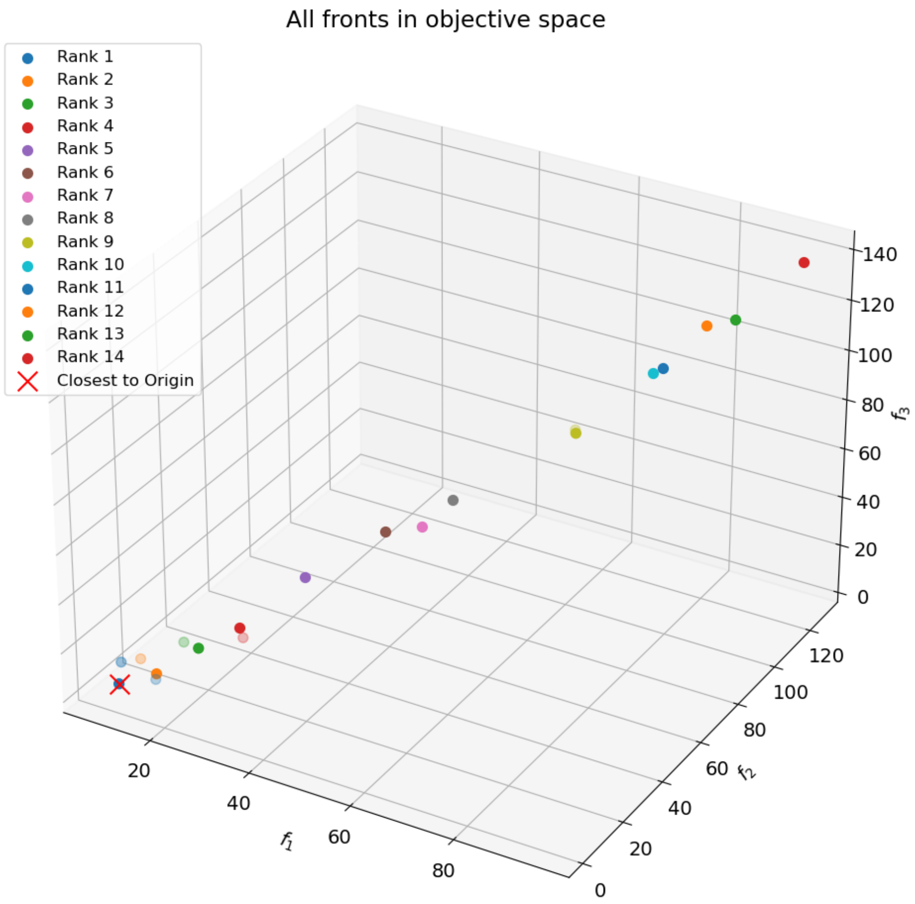
Part 3 – Optimization of parameters

- $E = 160\ GPa$ and $\nu = 0.3$ are fixed for all simulations
- Crossover:
  - η_{SBX} increases linearly, from 2 to 20
  - Probability of crossover: 0.9
- Mutation
  - η_{PM} increases linearly, from 2 to 20
  - Probability of mutation: 0.1
- Strain controlled simulations on cubic mesh
  - Strain amplitudes considered: 0.3, 0.5 and 0.6%
  - 3 cycles per strain amplitude



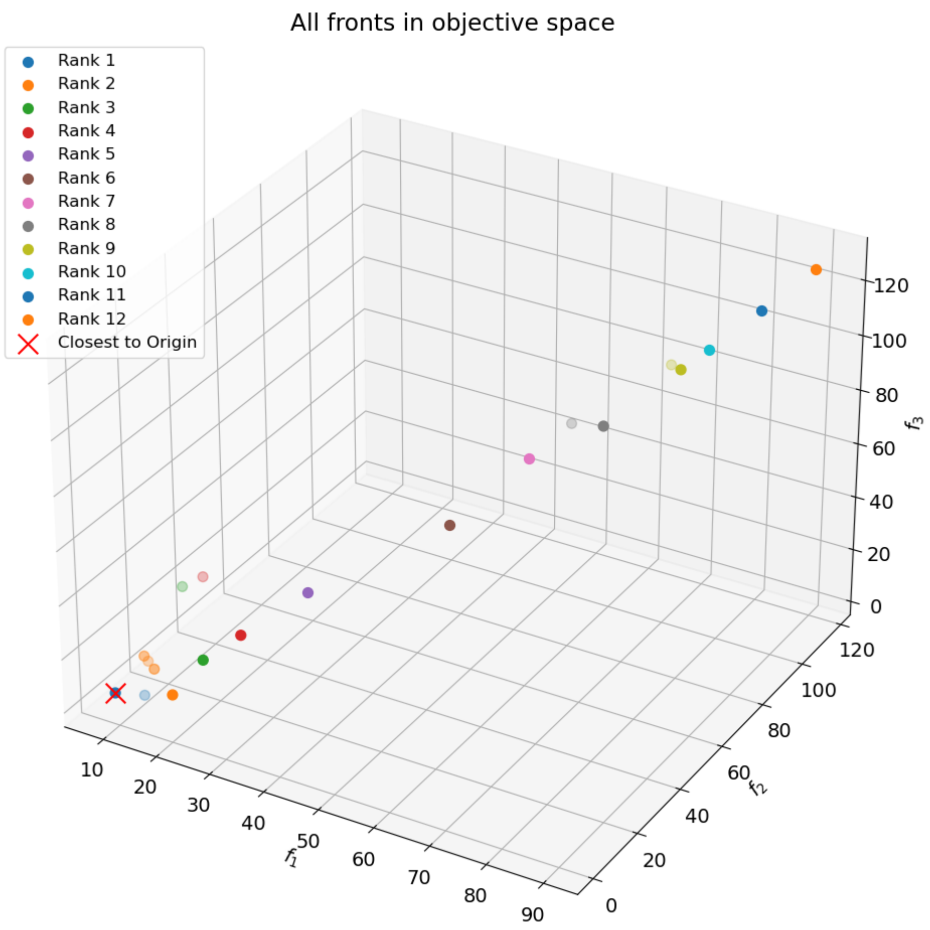
Part 3 – Optimization of parameters

- Objective space for all 3 runs
  - 1st run: $(n_{\text{gen}}, N) = (10, 20)$



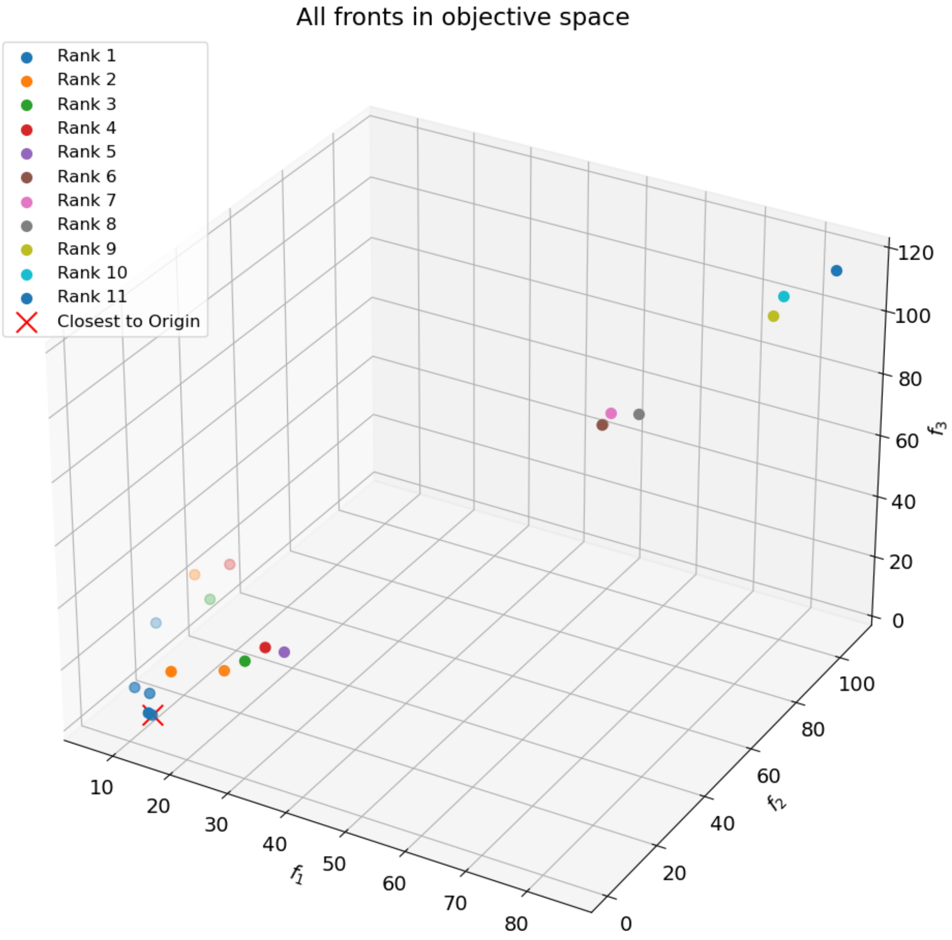
Part 3 – Optimization of parameters

- Objective space for all 3 runs
  - 1st run: $(n_{\text{gen}}, N) = (10, 20)$
  - 2nd and 3rd run: $(n_{\text{gen}}, N) = (20, 20)$



Part 3 – Optimization of parameters

- Objective space for all 3 runs
  - 1st run: $(n_{\text{gen}}, N) = (10, 20)$
  - 2nd and 3rd run: $(n_{\text{gen}}, N) = (20, 20)$
- Results tend to straight line
- Recommendations:
  - Increase n_{gen}, N and number of cycles
- Constraints:
  - Time limit of Cronos cluster



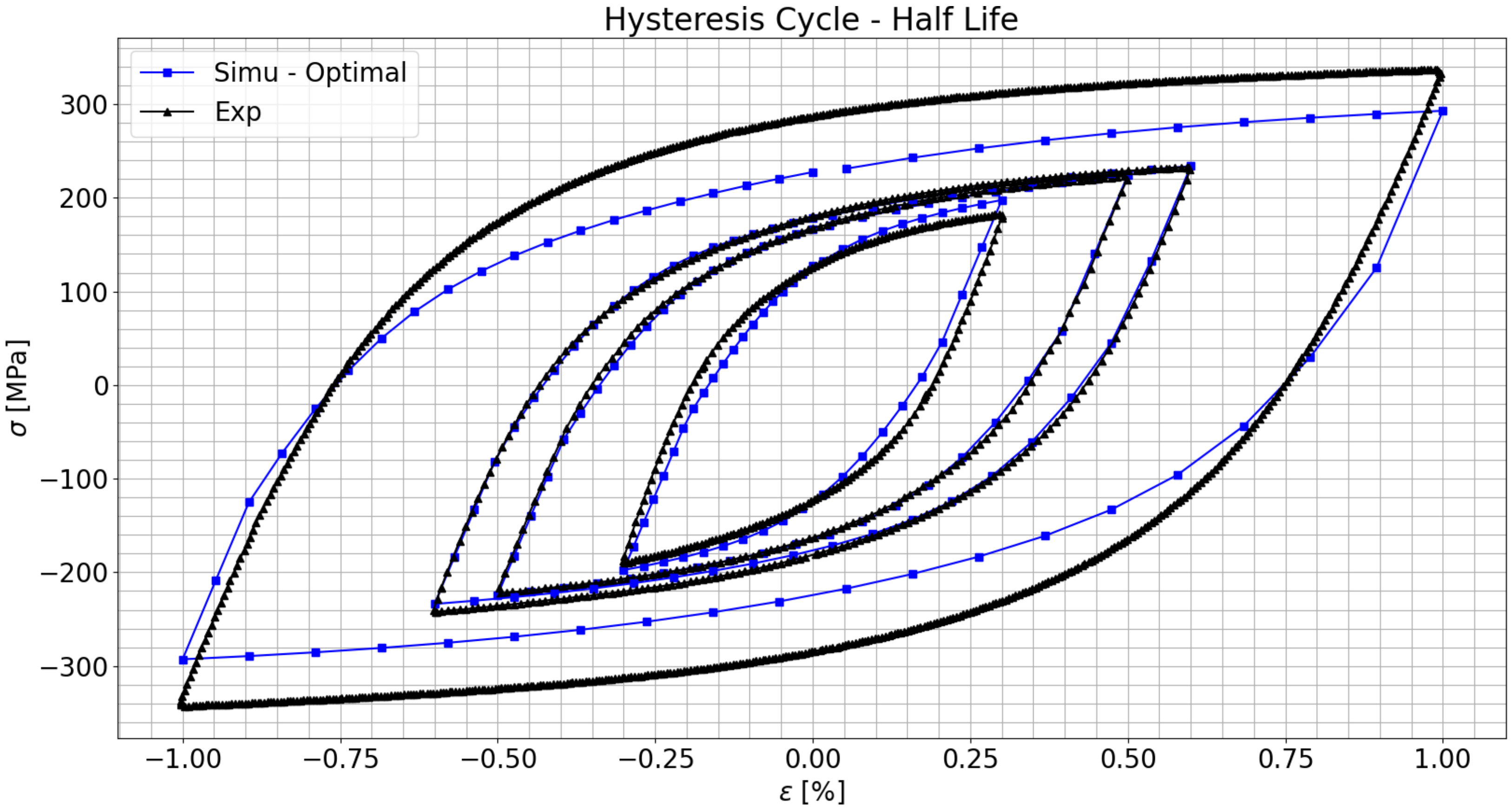
Part 3 – Optimization of parameters

- Obtained parameter set:

	Parameters	Zhang	OPT
Elasticity	E [GPa]	160	160
	ν	0.3	0.3
Kinematic Hardening	C_1 [MPa]	170000	165244.7511
	γ_1	1500	1985.0713
	C_2 [MPa]	25000	20257.3104
	γ_2	200	210.9897
Isotropic Hardening	R_0 [MPa]	110	81.4267
	b	10	4.5444

Part 3 – Optimization of parameters

- Hysteresis cycle comparison

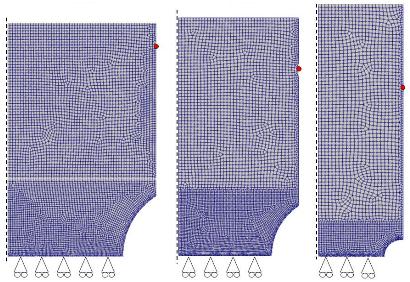


Part 4 –OPT parameters on specimens

- 1st analysis: diagnostic tests
  - FRF → 8 cycles / EDF → 3 cycles per step / KTU → 8 cycles per step

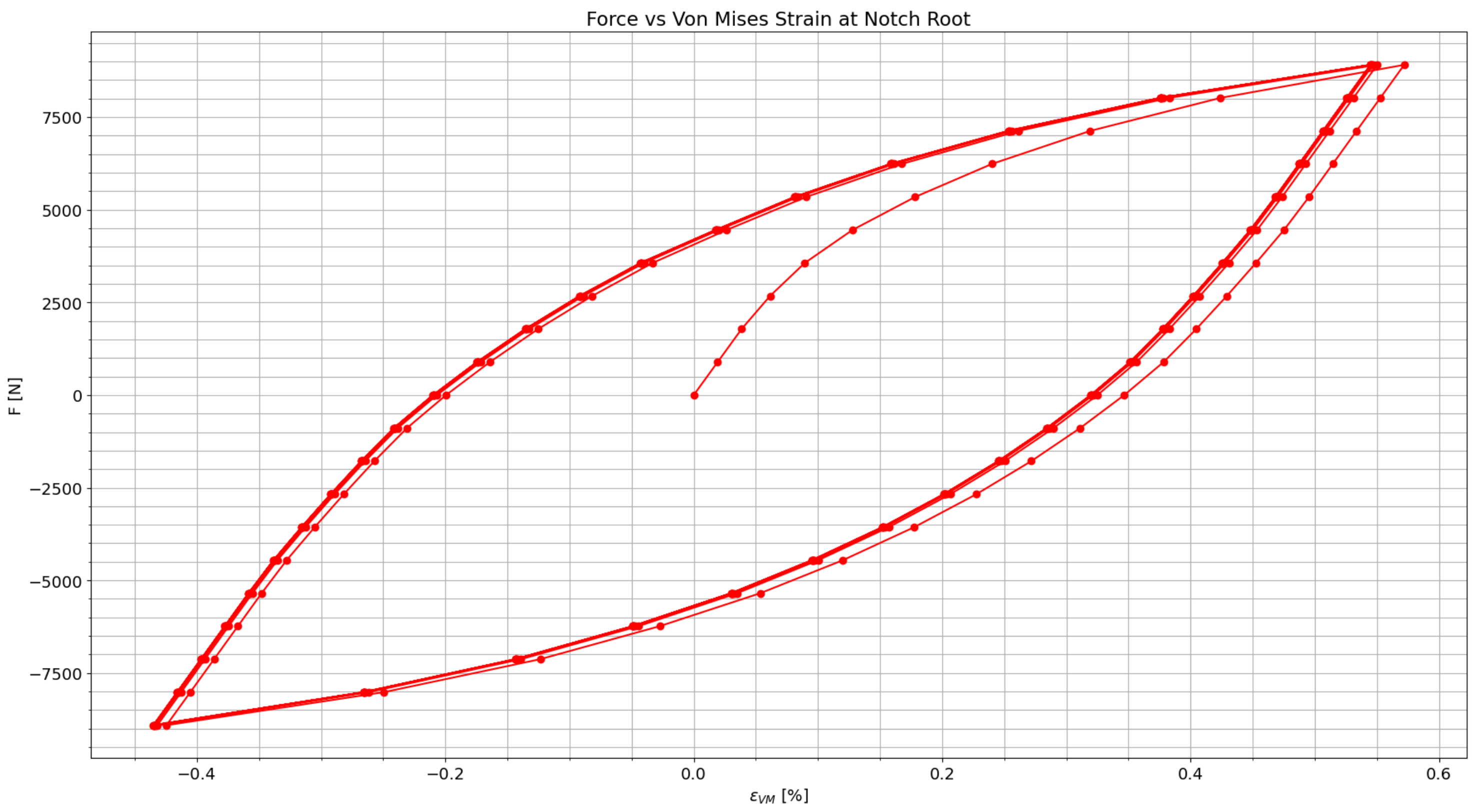
Lab	Step	F[N]	Target ε_{VM}[%]	ε_{VM}[%]-OPT	$\delta_{\varepsilon_{VM}}$[%]	Ext. amplitude[mm]	FEA-FRF [51]	FEA-CEA [51]	FEA-OPT	δ_y[%]-FRF	δ_y[%]-CEA	δ_y[%]-OPT
FRF	-	8908	0.6000	0.5450	-9.18	0.0240	0.02570	0.02590	0.02210	7.08	7.92	-7.88
EDF	1	4737	0.2000	0.2060	2.75	0.0080	0.00950	0.01120	0.01070	18.75	40.00	33.73
	2	6108	0.4000	0.3563	-10.93	0.0126	0.01710	0.01710	0.01680	35.71	35.71	33.10
	3	7147	0.6000	0.5580	-7.08	0.0238	0.02720	0.02200	0.02360	14.29	-7.56	$\boxed{-0.87}$
KTU	1	1521	0.2000	0.2100	5.00	0.0054	0.00510	0.00580	0.00575	-5.56	7.41	6.55
	2	2107	0.4000	0.4060	1.43	0.0100	0.0089	0.0104	0.0099	-11.00	4.00	$\boxed{-1.20}$
	3	2447	0.6000	0.5690	-5.17	0.0168	0.0125	0.0132	0.0127	-25.60	-21.43	-24.31

- Levels of error δ_y with the same order of magnitude as those obtained by Framatome and CEA
- In some cases, we get improved accuracy



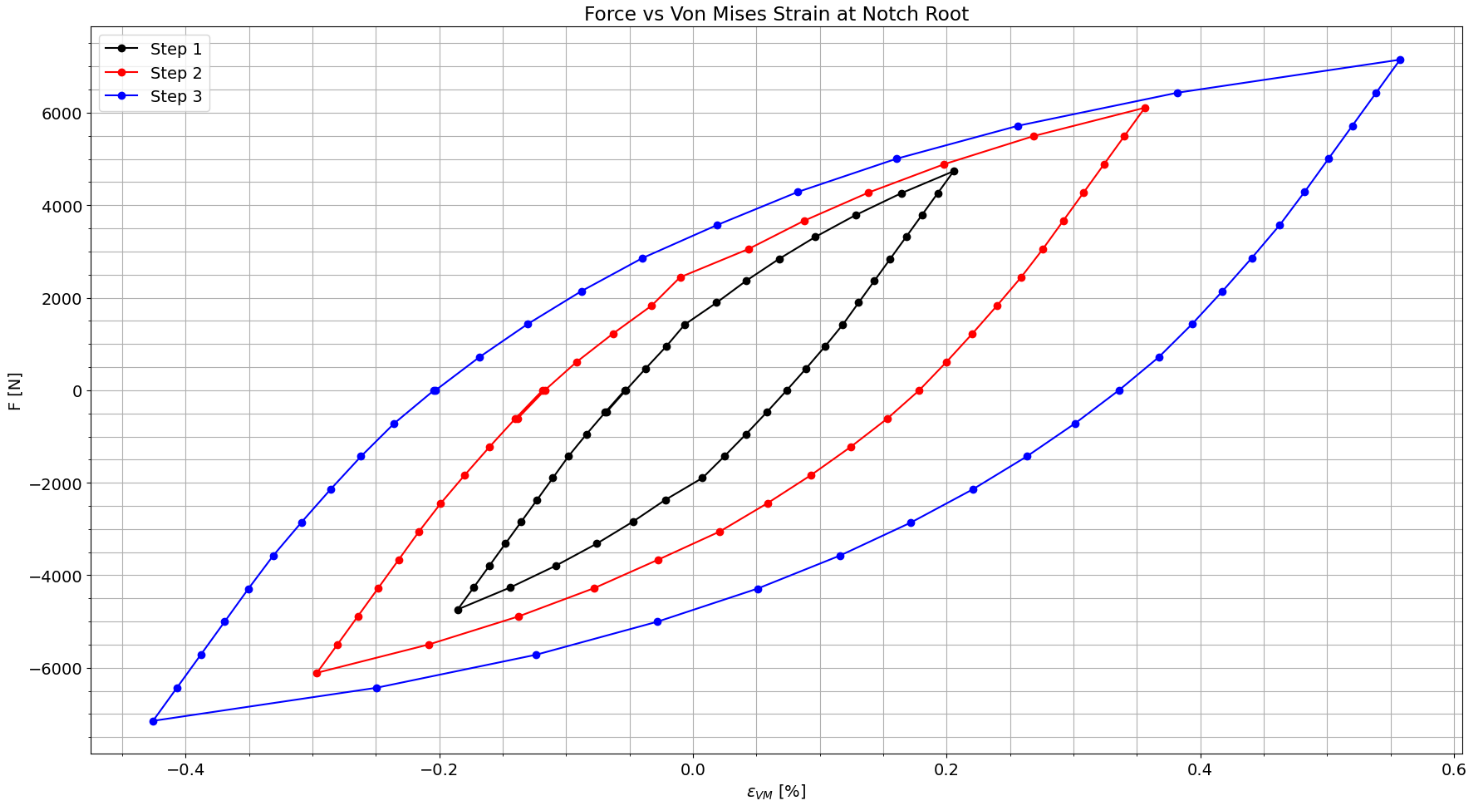
Part 4 –OPT parameters on specimens

- Possible to obtain hysteresis cycles at notch root



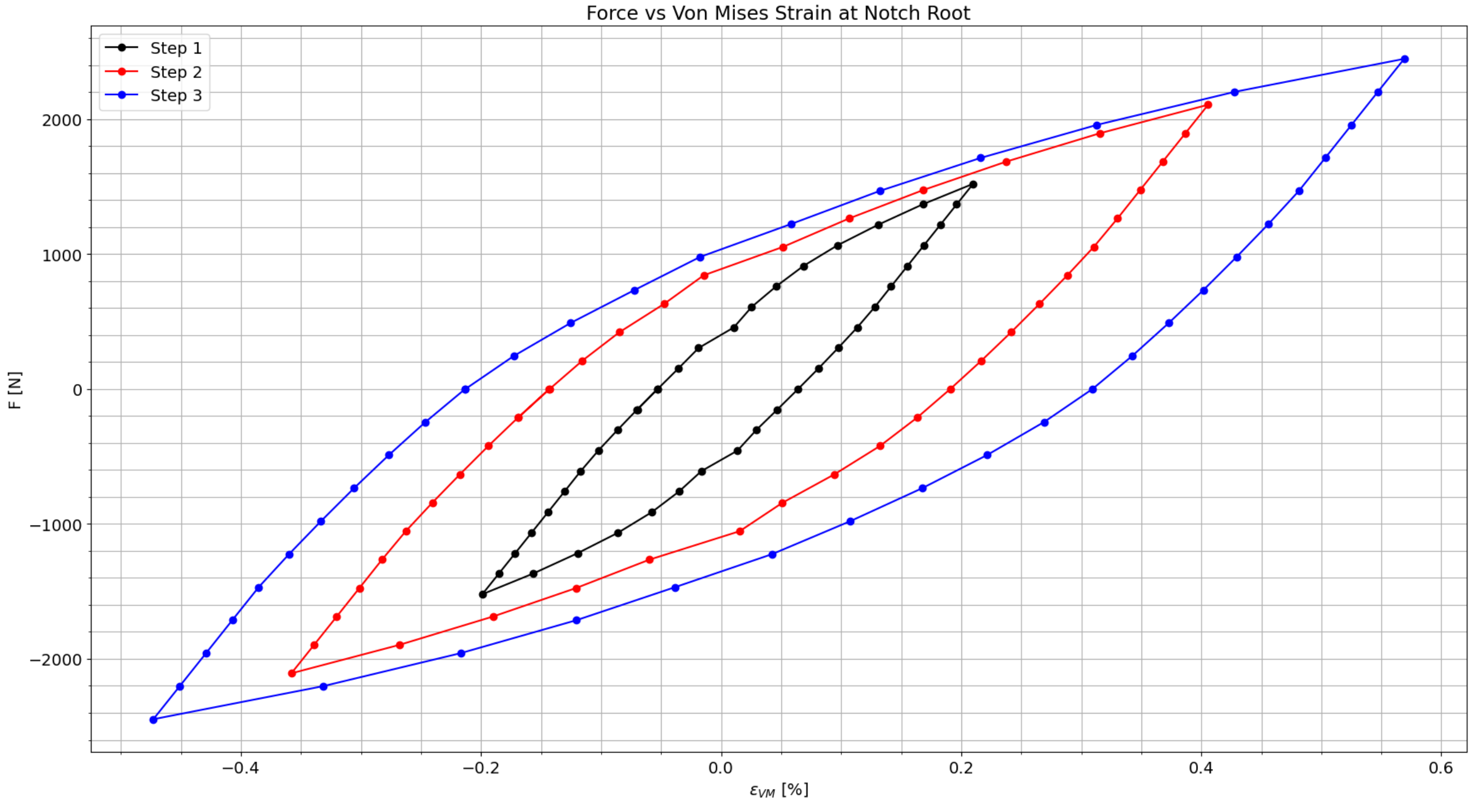
Part 4 –OPT parameters on specimens

- Possible to obtain hysteresis cycles at notch root



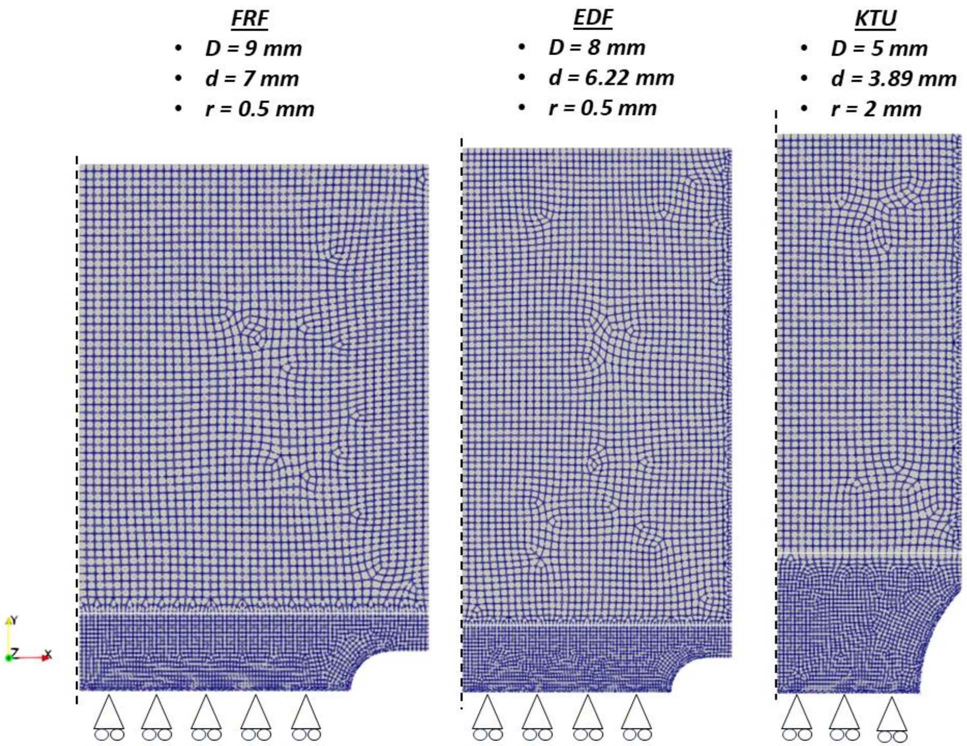
Part 4 –OPT parameters on specimens

- Possible to obtain hysteresis cycles at notch root
- $F \uparrow \Rightarrow \varepsilon_{VM} \uparrow$ and the cycle gets more asymmetrical



Part 4 –OPT parameters on specimens

- Implementation on specimens yet to be tested
  - New meshes:



Part 4 –OPT parameters on specimens

- Obtained results

Lab	D[mm]	d[mm]	r[mm]	F[N]	Target ε_{VM}[%]	ε_{VM}[%]-OPT	$\delta_{\varepsilon_{VM}}$[%]	Ext. length[mm]	Ext. amplitude[mm]	FEA-FRF[51]	FEA-OPT
FRF	9	7	2	6895	0.3000	0.2842	-5.27	12	0.008688	0.012594	0.013341
EDF/UC/VTT	8	6.22	2	5516	0.3000	0.2788	-7.07	12.5/12.5/12.0	-/-/0.0090	-/-/0.0128	0.0138/0.0138/0.0134
VTT	8	6.22	2	7147	0.6000	0.5487	-8.55	12	0.0198	0.0263	0.0227
KTU	5	3.89	0.5	1862	0.3000	0.3128	4.27	10	-	-	0.0079
FRF	9	7	0.5	5167	0.3000	0.3155	5.17	12	0.006212	0.006862	0.007687
FRF	9	7	0.5	7131	0.6000	0.6197	3.28	12	0.011160	0.012398	0.013247
EDF/UC/VTT	8	6.22	0.5	4212	0.3000	0.3148	4.93	12.5/12.5/12.0	0.006875/-/0.00600	0.007368/-/0.00705	0.008231/0.008231/0.00796
EDF/UC/VTT	8	6.22	0.5	5758	0.6000	0.6054	0.90	12.5/12.5/12.0	0.009875/-/0.0096	0.013360/-/0.0128	0.013991/0.013991/0.0135
KTU	5	3.89	2	2245	0.3000	0.2615	-12.83	10	0.010800	0.013715	0.011753
KTU	5	3.89	2	2958	0.6000	0.6024	0.4	10	-	-	0.021989

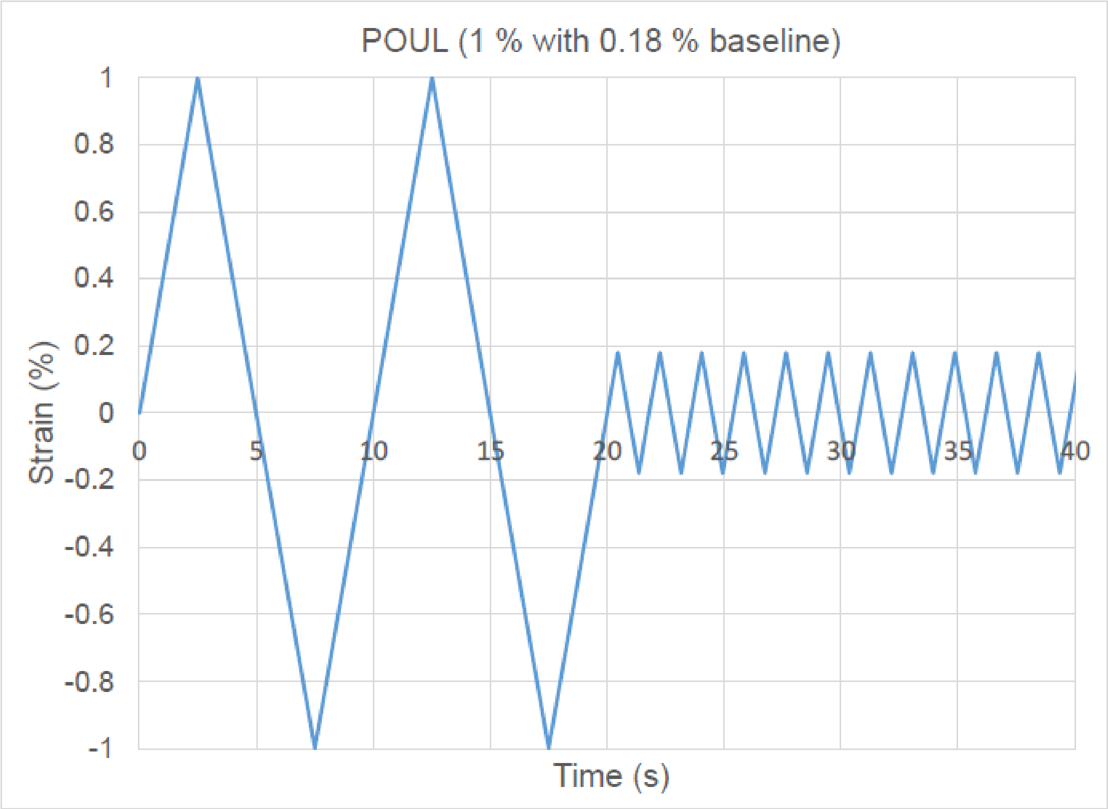
Lab	D[mm]	d[mm]	r[mm]	F[N]	δ[%]-FRF	δ[%]-OPT
FRF	9	7	2	6895	44.96	53.55
EDF/UC/VTT	8	6.22	2	5516	-/-/42.11	-/-/48.80
VTT	8	6.22	2	7147	32.92	$\boxed{14.47}$
KTU	5	3.89	0.5	1862	-	-
FRF	9	7	0.5	5167	10.4	23.66
FRF	9	7	0.5	7131	11.09	18.70
EDF/UC/VTT	8	6.22	0.5	4212	7.17/-/17.47	19.72/-/32.63
EDF/UC/VTT	8	6.22	0.5	5758	35.29/-/33.30	41.68/-/40.86
KTU	5	3.89	2	2245	26.99	$\boxed{8.828}$
KTU	5	3.89	2	2958	-	-

Part 4 –OPT parameters on specimens

- **Conclusion:**
  - Zhang and CEA parameter sets were not adequate for the half life stage of the 316L steel
  - Development of an optimization framework to find optimal parameter set
  - Results are promising, and there is now available numerical data for experiments yet to be conducted

Part 5 –Variable amplitude loading

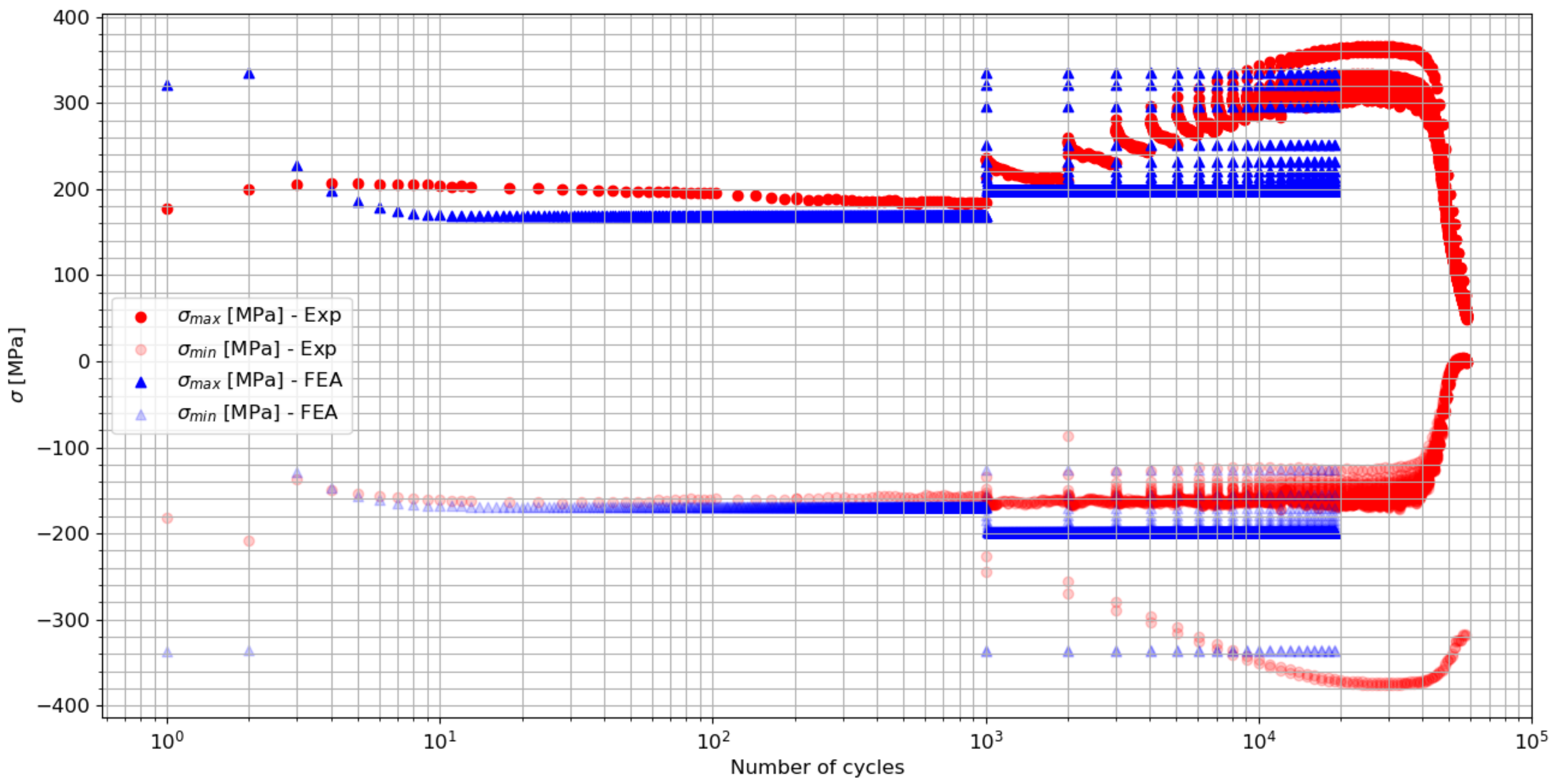
- Attempt to implement the optimized Chaboche model on Periodic Over-Underload (POUL) test
  - $\varepsilon = 1.0\%$ for 2 cycles
  - $\varepsilon = 0.18\%$ for 1000 cycles
- Extremely important, since real life components face variable amplitudes regularly



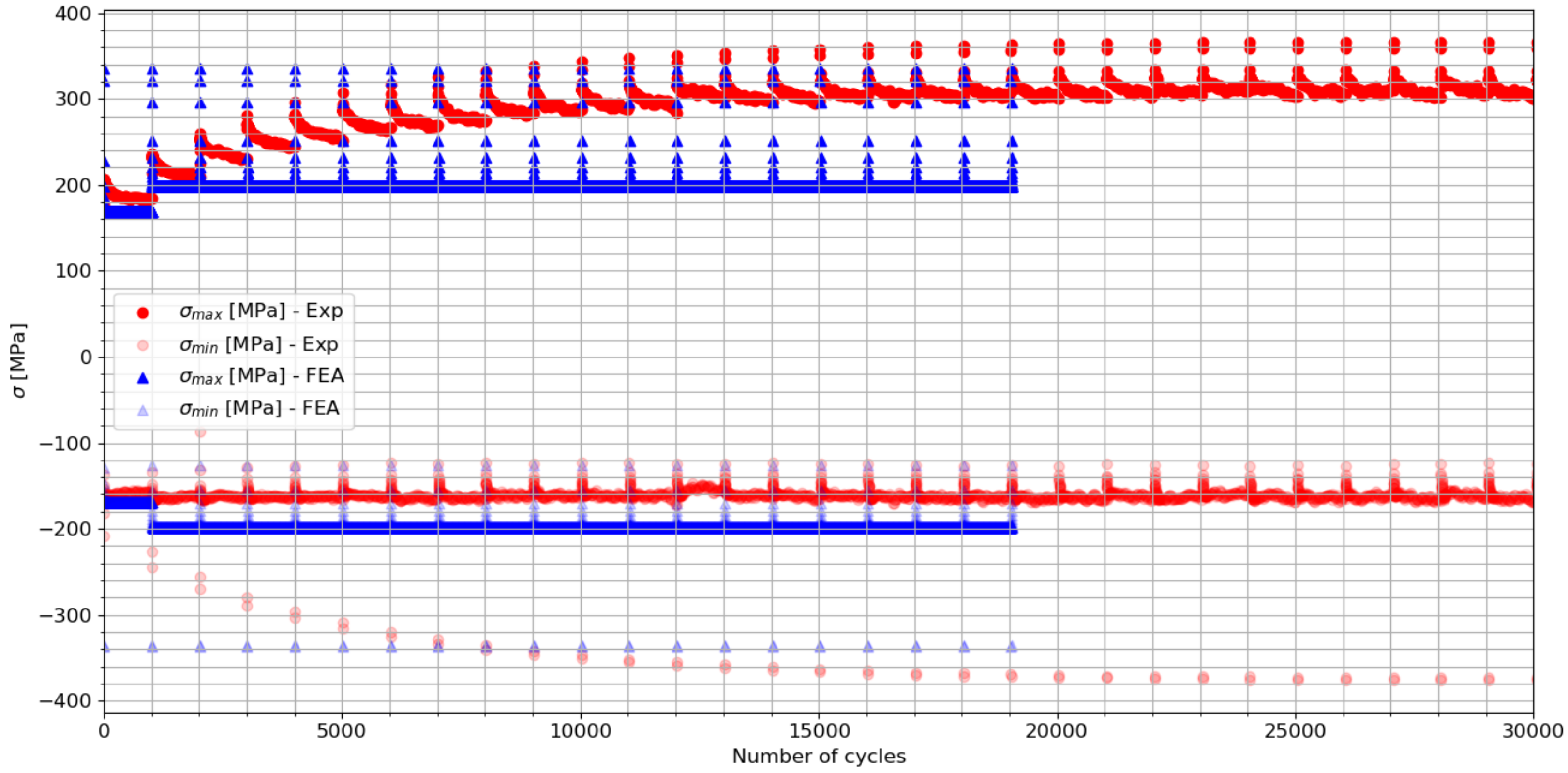
Part 5 –Variable amplitude loading

- **Strategy: implement Zhang parameters at $\Delta\varepsilon/2 = 1.0\%$ and OPT parameters at $\Delta\varepsilon/2 = 0.18\%$**
  - Attempt to extract the best out of the two parameter sets
- **Strain controlled simulations conducted on the cubic mesh**
- **Impossible to implement 1000 cycles at $\Delta\varepsilon/2 = 0.18\%$ per periodic repetition**
  - Solution: 20 cycles to achieve stabilization, then repeat the result until 1000 cycles for comparison with experimental results

Part 5 –Variable amplitude loading



Part 5 –Variable amplitude loading



Part 5 –Variable amplitude loading

- Conclusion:
  - Fairly good results for the first periodic repetition
  - FEA results not capturing progressive hardening
    - Zhang parameters designed to capture stress levels at maximum hardening or half life
  - Furthermore, OPT parameters are not capturing previous deformation state
    - Lack of history effect
  - Approach of multiple constitutive model parameter sets looks promising
  - Further exploration of this method could be interesting

6

Conclusion

Conclusion

- Initially, the objective was to reproduce INCEFA-SCALE fatigue tests
- Shift in research objective due to Chaboche model parameters not being suitable
- Implementation of NSGA-II evolutionary algorithm to tackle this problem
- Good FEA results obtained with multiple specimens
- Further work must be done on variable amplitude loading tests

Thank you for your attention!

Main references

- Zhang, Wen: Fatigue crack growth in large scale yielding condition. PhD thesis, Université Paris Saclay (COmUE), 2016.
- Deb, K., A. Pratap, S. Agarwal, and T. Meyarivan: A fast and elitist multiobjective genetic algorithm: Nsga-ii. IEEE Transactions on Evolutionary Computation, 6(2):182–197, 2002
- EDF: Incefa-scale report d4.2 - mo36 modelling progress. Unpublished project report, 2024.