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Cyclic Softening and Ratcheting of 42CrMo4+QT Steel: Experimental Basis for the FABEST LCF Benchmark

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Abstract: The reliable prediction of fatigue life under low-cycle fatigue conditions is a persistent challenge for high-strength steels used in critical components. This paper presents the experimental foundation for the FABEST LCF Competition, an international benchmark study focused on the cyclic behavior of 42CrMo4+QT steel, organized within the FABER COST Action. The experimental campaign thoroughly characterizes the material's distinct cyclic softening behavior. It investigates complex phenomena critical for accurate modeling, such as ratcheting under asymmetric stress-controlled cycles and mean stress relaxation induced by pre-straining. This high-quality dataset serves as the basis for a "blind prediction" competition designed to validate advanced cyclic plasticity and fatigue damage models.

Keywords: low-cycle fatigue; cyclic stress-strain curve; ratcheting; mean stress relaxation; FABEST.

1 Introduction

The prediction of fatigue life for metallic alloys in the low-cycle fatigue (LCF) regime remains a significant challenge, even under constant amplitude loading. Several complex phenomena must be accurately captured. First, neglecting transient effects, such as cyclic hardening or softening, can significantly compromise prediction accuracy. Second, under stress-controlled loading, the progressive accumulation of plastic strain due to a non-zero mean stress, also known as cyclic creep or ratcheting, can shorten fatigue life, particularly at high stress levels [1]. This phenomenon is particularly damaging as it can lead to failure by excessive deformation or by accelerating fatigue crack initiation. Similarly, under strain-controlled conditions with a non-zero mean strain, mean stress relaxation occurs and has a significant impact on fatigue life, especially at lower strain amplitudes. Advanced cyclic plasticity models often share key parameters that influence both ratcheting and mean stress relaxation [2]. Consequently, the accurate and simultaneous prediction of both phenomena using a single, unified set of parameters remains a major scientific challenge.

The accurate prediction of LCF life requires high-quality, consistently processed experimental data, which serves as a foundation for both material characterization and the validation of numerical models. To address this challenge through international collaboration, the COST Action CA23109 FABER (Fatigue Benchmark Repository) was established to support the sharing, analysis, and accessibility of research data among engineers and scientists [3]. Within this action, Working Group 4.7 (WG4.7) is specifically dedicated to LCF phenomena. A significant part of its effort is focused on standardizing the evaluation of complex LCF tests, including both uniaxial and axial-torsional loading conditions. A crucial step towards this standardization has been the development of an open-source toolset in Python, designed to automate and unify the post-processing of experimental data. These tools, detailed by Natarajan et al. in [4], provide a consistent framework for determining fatigue parameters from LCF tests, thereby eliminating inconsistencies from manual evaluation and ensuring data interoperability across the project. These Python codes will be made available to the public during the various phases of the FABER project.

Building upon this standardized evaluation framework, this paper presents the experimental foundation for the upcoming “FABEST in LCF” Competition. The competition focuses on 42CrMo4+QT steel, a high-strength alloy widely used in industry and known for its complex cyclic response, making it an ideal candidate for a benchmark study. The goal is to challenge the current generation of computational models by providing a high-quality dataset that captures several complex material phenomena.

This paper is structured to serve as the definitive guide for the competition. It will first outline the scientific aims, rules, and timeline of the benchmark. Subsequently, it will present the complete experimental calibration dataset in detail. This dataset includes tests specifically designed to characterize the material's distinct cyclic softening, mean stress relaxation, and ratcheting behavior. By providing this robust foundation, we aim to foster the development and validation of advanced cyclic plasticity and fatigue life prediction models.

2 The FABEST LCF Competition

This paper serves as the official announcement and foundational document for the “FABEST in LCF” Competition. This international benchmark study is designed to assess the current state-of-the-art in modeling and life prediction for steels under complex cyclic loading. The competition provides a unique opportunity for researchers from both academia and industry to test their computational models against a new, high-quality, and independently verified experimental dataset.

2.1 Context within the FABER COST Action

The competition is a key deliverable of the COST Action CA23109 FABER. The primary goal of FABER is to support the sharing, analysis, and accessibility of research data to create a reliable, open-access repository for the fatigue community. Within this framework, Working Group 4.7 (WG4.7) is specifically dedicated to LCF phenomena, and this competition represents its flagship initiative to generate a high-value benchmark dataset.

2.2 Scientific Aims and Experimental Framework

The benchmark is centered on the behavior of 42CrMo4+QT high-strength steel [5].

The competition is designed to address two key research questions:

- Is the current generation of advanced cyclic plasticity models capable of describing both ratcheting and mean stress relaxation with a single, unified set of material parameters?
- What is the most suitable fatigue life prediction method for uniaxial loading that can accurately account for the combined effects of both these phenomena?

Furthermore, the benchmark will provide significant insight into the importance of incorporating transient cyclic softening for accurate life prediction. To investigate these questions, the competition is structured around a "blind prediction" format with a dedicated calibration and validation set.

2.2.1 Calibration Set - Data Provided to Participants

The following experimental datasets will be provided to all participants:

- Strain-controlled tests:
    - Case 1: Baseline strain-life (*e*-*N*) and cyclic stress-strain (CSS) curves for fully reversed loading ($R_\varepsilon = \varepsilon_{min}/\varepsilon_{max} = -1$).
    - Case 2: A full dataset for tests with a constant mean strain of +0.5 % to characterize mean stress relaxation.
- Stress-controlled tests:
    - Case 3: A full lifetime curve for a stress ratio of $R_\sigma = \sigma_{min}/\sigma_{max} = -0.5$ to characterize the material's ratcheting response.

While the full calibration dataset is provided for model tuning, the competition evaluation is strictly limited to 9 mandatory experiments (Cases 1 and 2: 0.4 %, 0.75 %, and 1.25 % of strain amplitude, Case 3: 675 MPa, 731 MPa, 790 MPa of stress amplitude).

2.2.2 Validation Set - Prediction Target

Participants will be challenged to predict the material's response and fatigue life for two new loading scenarios:

- Strain-controlled tests (Case 4): A set of tests with a more severe mean strain of +1.0%.
- Stress-controlled tests (Case 5): A set of tests with a different stress ratio of $R_\sigma = -0.7$.

Eight levels of loading will be considered to get the lifetime curve in both cases (4 and 5). While the full calibration dataset is provided for model tuning, the competition evaluation is strictly limited to 17 mandatory experiments.

In order to have clear and transparent evaluation process, the predictions have to be performed for:

- Case 4: 0.4%, 0.6%, 0.85%, and 1.25% of strain amplitude.
- Case 5: 700 MPa, 750 MPa, 800 MPa, and 850 MPa of stress amplitude.

2.2.3 Data Structure

The open-source Python code mentioned in the introduction was applied to extract important fatigue parameters and damage indicators. The most important results are summarized in a PDF protocol generated from Python for each experiment separately.

For each LCF test, the entire history of following quantities (see Fig. 1) is available in *amp_mean_values.CSV*:

- strain amplitude ε_a,
- mean strain ε_m,
- stress amplitude σ_a,
- mean stress σ_m,
- dynamic modulus in compressive branch of hysteresis loop E_{dyn}^{com},
- dynamic modulus in tensile branch of hysteresis loop E_{dyn}^{ten},
- cyclic yield stress Y_{cyclic}, evaluated for 0.05% plastic strain offset measured from the reversal point,
- plastic work per cycle ΔW_p , defined as $\Delta W_p = \oint_{(cycle)} \sigma \, d\varepsilon_p$, where ε_p is the axial plastic strain.

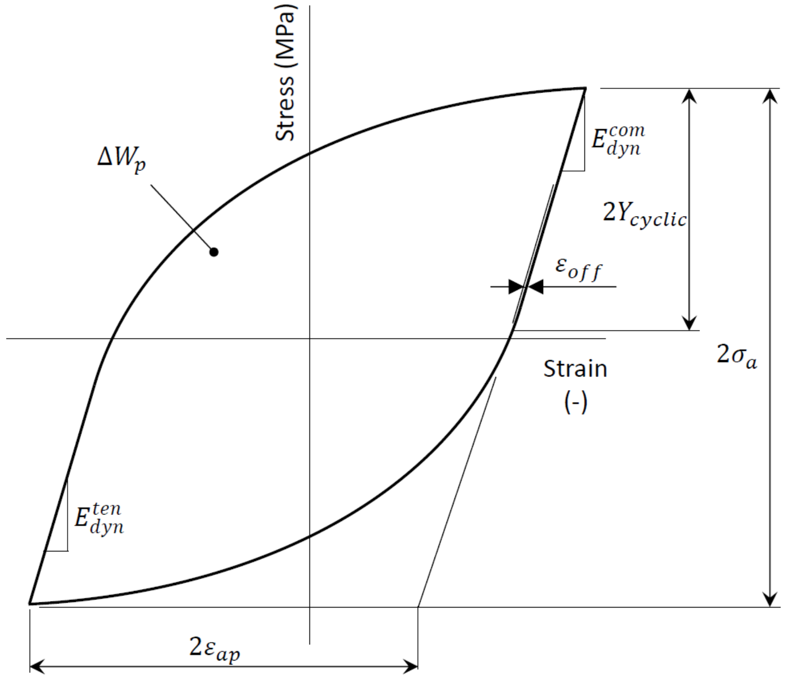


Fig. 1: A scheme of hysteresis loop with explanation of evaluated quantities.

Complete history is provided in *For_FEM.CSV* file containing time, strain, stress and cycle values. The most important quantities evaluated at half-life are reported in *output_half.CSV*. In order to have the same approach for determination of number of cycles to failure in strain-controlled as well as stress-controlled tests, the fatigue life (N_f^{E10}) is defined by a 10% decrease in the dynamic modulus (E_{dyn}^{com}). In calibration Cases 1–3, the specific N_f values are listed in the experimental protocols distributed for each fatigue curve separately.

2.3 Timeline

The competition will follow a strict timeline:

- *Official Launch*: The competition will be officially launched during the 1st FABER Conference (May 5-6, 2026).
- *Data Release*: The complete calibration dataset, CSV templates, and the EAN2026 pre-print are available at the ZENODO repository: **https://doi.org/10.5281/zenodo.19896970**.
- *Submission Deadline*: The deadline for submitting all predictions will be October 31, 2026.

2.4 Rules

Participants will be required to submit their results in a specified format. To ensure a clear focus on individual or small-team contributions, each submission is limited to a maximum of two authors (typically a PhD student and their supervisor). The competition will be evaluated in two distinct categories:

- *Category A - Cyclic Plasticity Modeling*: Prediction of the stabilized and transient cyclic stress-strain response (ε_a, ε_m, σ_a, σ_m and cycle number for required cycles separated by semicolons). Data should be exported for specific logarithmic cycles (e.g., 1, 2, 5, 10, 20, 50, 100, 200, 500, 1000, 2000, and 5000). It should be noted that the maximal number of cycles in simulation should be lower than N_f in calibration tests, but N_f is not known for validation cases. Therefore, required maximum number of cycles for each mandatory test is specified in Tab. 1.

Tab. 1: Definition of mandatory experiments.

Case ID	**Control Type**	**Loading Condition**	**Level**	**Amplitude**	**Number of cycles in simulation *N***
Case 1 (Calibration)	Strain-controlled	$R_\varepsilon = -1$	High Amp	**1.25 %**	**200**
			Medium Amp	**0.75 %**	**1000**
			Low Amp	**0.4 %**	**5000**
Case 2 (Calibration)	Strain-controlled	$\varepsilon_m = +0.5\%$	High Amp	**1.25 %**	**200**
			Medium Amp	**0.75 %**	**1000**
			Low Amp	**0.4 %**	**5000**
Case 3 (Calibration)	Stress-controlled	$R_\sigma = -0.5$	High Amp	**790 MPa**	**100**
			Medium Amp	**731 MPa**	**1000**
			Low Amp	**675 MPa**	**5000**
Case 4 (**BLIND**)	Strain-controlled	$\varepsilon_m = +1.0\%$	Level A	**1.25 %**	**100**
			Level B	**0.85 %**	**500**
			Level C	**0.6 %**	**1000**
			Level D	**0.4 %**	**5000**
Case 5 (**BLIND**)	Stress-controlled	$R_\sigma = -0.7$	Level A	**850 MPa**	**100**
			Level B	**800 MPa**	**500**
			Level C	**750 MPa**	**2000**
			Level D	**700 MPa**	**5000**

- *Category B – Fatigue Life Prediction*: Prediction of N_f for cases 1 and 2 (N_f^{pred}). Predictions for all mandatory tests will be submitted in the form of a single CSV file, where N_f^{pred} and *ID* of experiment will be separated by semicolons for all 17 mandatory experiments.

For both categories a description of the approach used is necessary in a PDF document (max. 2 pages, the template will be provided by July 17th, 2026). The exact evaluation metric, likely based on the scatter band of predicted vs. experimental fatigue lives, is detailed in the official competition documentation.

As a significant incentive, the participants with the top three submissions in each category will be invited to co-author a high-impact review paper summarizing the competition's outcomes, which will be prepared within WG4.7 LCF. The organizers reserve the right to invite authors of other interesting studies to contribute as well. Main Prizes will be High-end mobile devices (iPhone/iPad) for the winners of each category, sponsored by our Main Prize Partners.

3 LCF testing procedures and calibration set description

All experimental tests for the calibration set were performed at VŠB - Technical University of Ostrava on a biaxial fatigue testing machine (LabControl 100kN/1000Nm), with an EPSILON TECH 3442 axial extensometer used for strain control and measurement (10 mm gauge length), to ensure maximum consistency. Each of the three fatigue curves presented is based on data from eight specimens (different level of strain/stress amplitude for each of them). The geometry of the specimen is detailed in Fig. 2. A surface roughness of approximately Ra 1.6 μm was achieved through a fine final turning process.

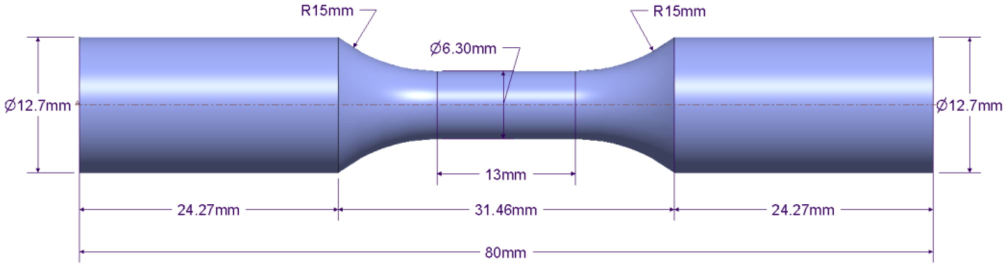


Fig. 2: Geometry of specimen.

3.1 Strain controlled LCF testing

The baseline low-cycle fatigue behavior of the 42CrMo4+QT steel was characterized through fully reversed ($R_\varepsilon = -1$) uniaxial strain-controlled tests, conducted at a strain rate of 0.01 s^{-1}. The results, presented in Fig. 3, serve as the primary dataset for calibrating fundamental fatigue models and represent the first part of the calibration set for the FABEST competition.

The material's behavior is described by the Ramberg-Osgood (RO) equation for the cyclic stress-strain curve (CSSC)

$$\varepsilon_a = \varepsilon_{ae} + \varepsilon_{ap} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{1/n'} \tag{1}$$

and the Manson-Coffin-Basquin (MCB) equation for the strain-life curve

$$\varepsilon_a = \varepsilon_{ae} + \varepsilon_{ap} = \frac{\sigma'_f}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c \tag{2}$$

To ensure full compatibility between these two descriptions:

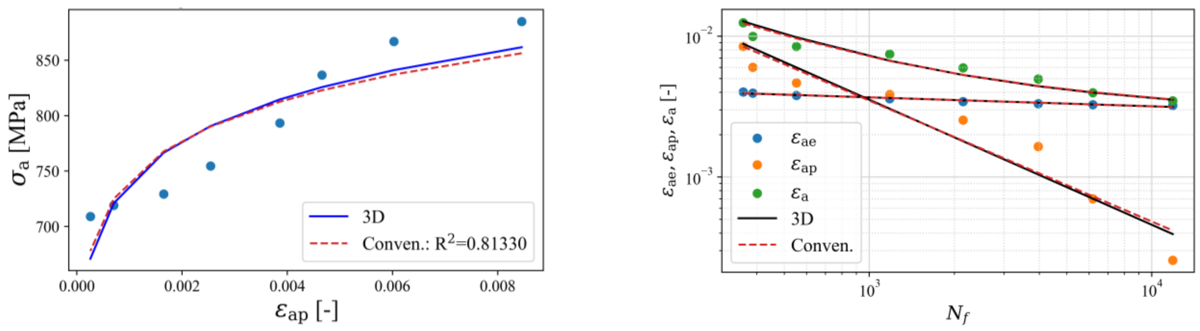
$$K' = \frac{\sigma'_f}{{\varepsilon'_f}^{n'}}, n' = \frac{b}{c} \tag{3}$$

all six material parameters $\sigma_f', \varepsilon_f', b, c, K', n'$ were identified simultaneously using the 3D regression method proposed by Niesłony et al. [6]. For completeness, the source data (protocols prepared in Python) also reports alternative parameters determined using the conventional method of three independent regressions.

3.1.1 Zero mean strain

Fig. 3a shows the cyclic stress-strain curve, which represents the stabilized stress-strain response of the material. A notable characteristic of the 42CrMo4+QT steel is its distinct cyclic softening behavior. For all applied strain amplitudes, the material exhibited a significant decrease in stress response from the first cycle, stabilizing after a certain number of cycles. The figure presents two Ramberg-Osgood model fits to the stabilized experimental data points. The solid blue line represents the fit obtained using the consistent 3D method, while the dashed red line corresponds to the conventional method of independent regressions. However, it is important to note that the experimental CSSC shows significant deviation from the simple power-law relationship, with differences in stress amplitude reaching up to 50 MPa. This discrepancy presents a key challenge for the competition, as accurately capturing the CSSC is crucial for any advanced fatigue life prediction model.

The strain-life behavior of the material is presented in Fig. 3b. This plot shows the total strain amplitude (ε_a) as a function of the number of cycles to failure (N_f), along with its decomposition into elastic (ε_{ae}) and plastic (ε_{ap}) components. The curves were fitted using the Manson-Coffin-Basquin (MCB) relationship, where a Young's modulus of E = 210 GPa was used in the identification procedure. However, a closer inspection of the plot reveals a significant scatter of the experimental data, particularly in the plastic strain component, around the fitted lines. This deviation clearly indicates that even this standard strain-based approach is insufficient for a reliable fatigue life prediction for this material, further highlighting the central challenge addressed by the FABEST competition.



a) Cyclic stress-strain curve

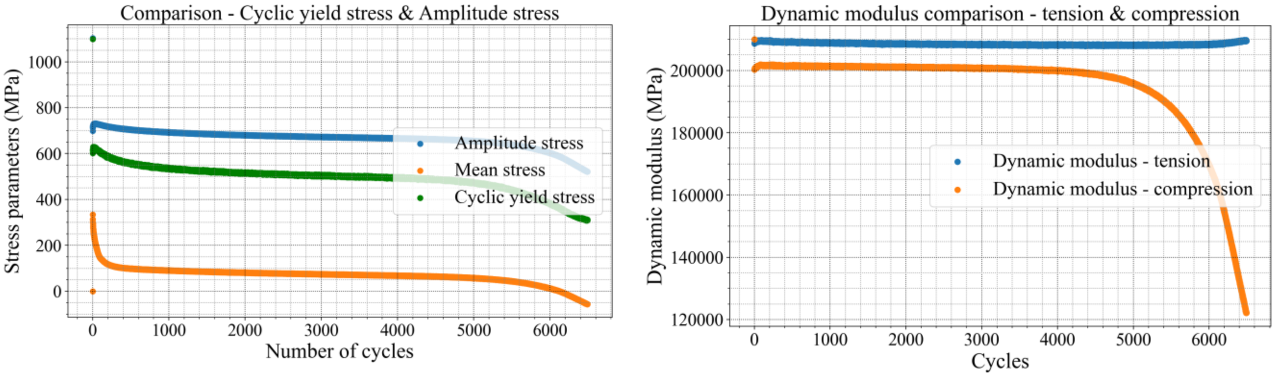
b) *e-N* curve

Fig. 3: Results of LCF tests performed on 42CrMo4+QT under 0.01s^{-1} strain rate and zero mean strain.

3.1.2 0.5 % mean strain

To investigate the effect of mean stress on fatigue life, a second series of strain-controlled tests was conducted with a constant mean strain of +0.5 %. As is typical for this type of loading, the material exhibited significant mean stress relaxation, as documented in Fig. 4a. An example of the significant decrease of the tensile dynamic modulus at the end of a test is presented in Fig. 4b.

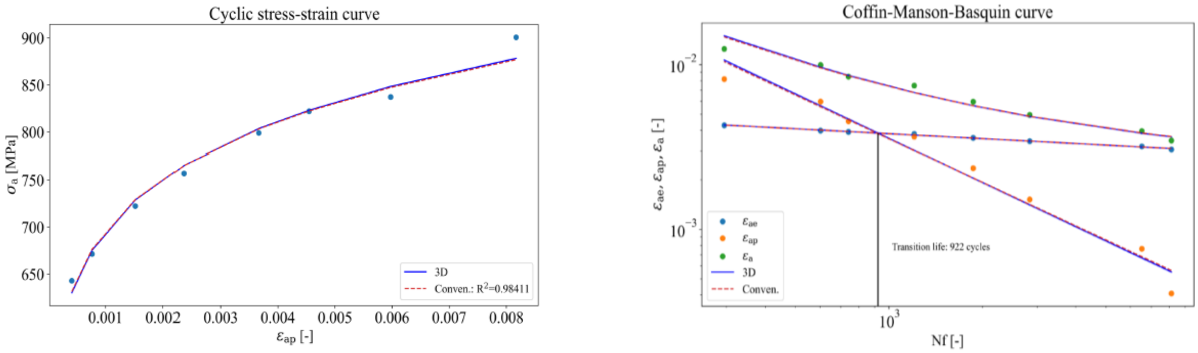
It should be mentioned that the initial tensile mean stress rapidly decreased within the first few cycles, approaching a fully relaxed state (zero mean stress) for tests at strain amplitudes higher than 0.5%. However, at lower strain amplitudes, a stabilized tensile mean stress persisted, which has a known detrimental effect on fatigue life. Fig. 5b illustrates this life reduction, which is most pronounced in the high-cycle region where the mean stress effect is dominant. Notably, for this loading case, the Ramberg-Osgood approximation shows a much better correlation with the experimental CSSC (Fig. 5a) compared to the zero mean strain case.



a) Mean stress relaxation and cyclic softening behavior

b) Dynamic moduli evolution with cycling

Fig. 4: Results from the LCF test performed at 0.4 % of strain amplitude and 0.5 % mean strain.



a) Cyclic stress-strain curve

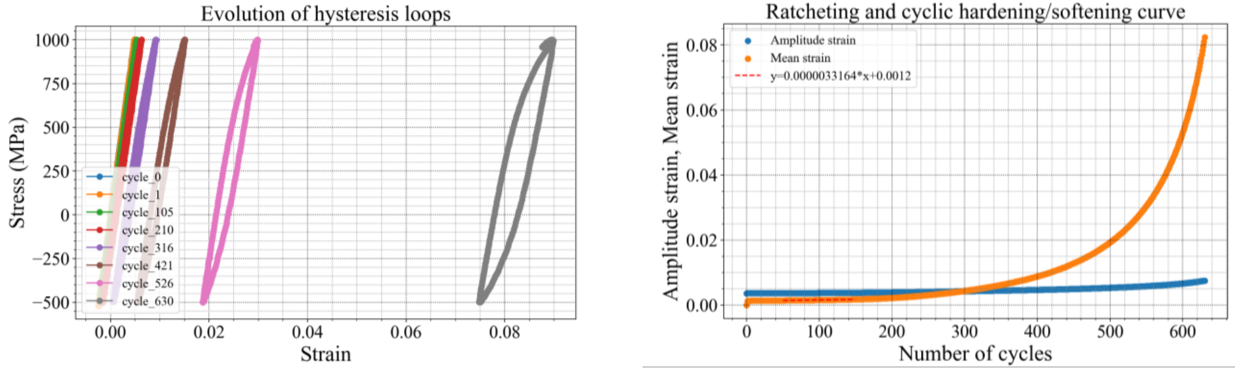
b) *e-N* curve

Fig. 5: Results of LCF tests performed on 42CrMo4+QT under 0.01s^{-1} strain rate and 0.5 % mean strain.

3.2 Stress controlled LCF testing

The final part of the calibration set focuses on the material's response under stress-controlled loading with a non-zero mean stress ($R_\sigma = -0.5$). This condition is designed to induce ratcheting. An example of main outputs is presented in Fig. 6. Considering the case with mean stress of 250 MPa and the stress amplitude 750 MPa, chosen hysteresis loops are presented in Fig. 6a, whereas almost elastic behavior in initial cycles is apparent. The accumulation of plastic deformation characterized as the evolution of mean strain is visible in Fig. 6b.

Fig. 7 presents the resulting stress-life (S-N) curve for the $R_\sigma = -0.5$ tests. This curve is essential for calibrating advanced fatigue models that can account for the detrimental effect of both the stress amplitude and the mean stress on fatigue life.



a) Representative hysteresis loops

b) Evolution of strain amplitude and mean strain

Fig. 6: Results from the ratcheting test performed at 750 MPa of stress amplitude and 250 MPa mean stress.

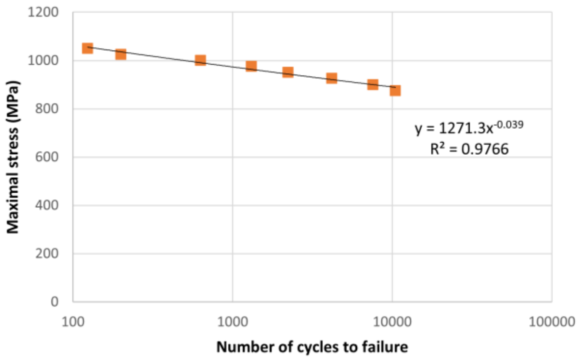


Fig. 7: S-N curve for the $R_\sigma = -0.5$ tests performed on 42CrMo4+QT.

4 Conclusion

This paper has presented the comprehensive experimental foundation for the FABEST Low-Cycle Fatigue (LCF) Competition, an international benchmark organized within the FABER COST Action. A robust calibration dataset for 42CrMo4+QT steel has been detailed, highlighting the material's distinct cyclic softening, mean stress relaxation, and ratcheting behavior. These complex phenomena, coupled with observed deviations from standard material models like Ramberg-Osgood, present a significant scientific challenge. The competition's framework, including the "blind prediction" format, clear timeline, and evaluation rules, has been established to provide a transparent and credible platform for the validation of advanced cyclic plasticity and fatigue damage models. By inviting broad participation from the research community, this initiative aims to advance the state-of-the-art in LCF life prediction and foster the development of more reliable engineering tools.

Acknowledgement

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