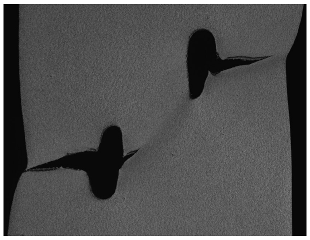
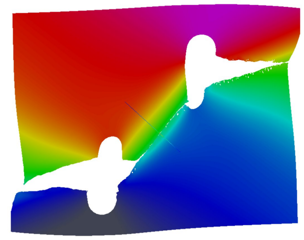


Data-Driven exploration of Ductile fracture response



Ductile Fracture of 316L Stainless steel at CEA

The French Alternative Energies and Atomic Energy Commission (CEA) plays a crucial role in ensuring the safety of nuclear installations such as Pressurized Water Reactors (PWRs). One of the key aspects of this mission is the analysis of severe accident scenarios, such as the Loss of Coolant Accident (LOCA). During such events, the sudden depressurization of the primary circuit can lead to structural failures, including pipe whip [1]. To accurately predict these phenomena and improve safety margins, a detailed understanding of the involved material behavior is essential.

Stainless steel 316 is widely used in the nuclear industry - e.g. for piping systems - due to its excellent mechanical properties and resistance against corrosion and irradiation. Its failure mode is known to be ductile, i.e. it is preceded by significant plastic deformation. Such behaviors can be influenced by various factors such as temperature, strain rate, and environmental conditions.

The primary goal of this thesis is to develop a HPC-scalable tool aiming to construct a reliable database that will serve as a foundation for assessing and developing constitutive behavior relations, particularly for large strain plasticity and ductile fracture. The innovative approach adopted in this research is model-free, aiming to identify dual quantities such as mechanical stresses without relying on predefined constitutive laws.

Background of Model-Free Data Driven Identification

The formulation of continuum mechanics problems involves two types of governing equations. First, there are the equilibrium (or motion) equations and the compatibility conditions (displacement-strain relationships), which are free from uncertainty since they are based widely-accepted, universal principle of mechanics. On the other hand, constitutive relations provide the relation between dual and primal variables (stress and strain, respectively). Beside this, constitutive relations also serve some more several purposes. Elaborating such relations is usually a complex task, from the collection of experimental data, to the postulation of mathematical rules and then data-fitting process while respecting thermodynamic consistencies. This task is even more difficult for complex behaviour like ductile failure that induces phenomenon like necking making useless usual material characterization approaches.

Since the early development of digital cameras, full field measurement techniques (e.g. Digital image correlation (DIC)) based on digital imaging started revolutionizing the identification of constitutive relation. Accessing a full kinematic field over the surface of the sample allows for breaking the bottleneck of standard testing of materials. Inverse methods of estimating the best parameters of a pre-supposed constitutive law has been the focus of an intensive research effort during the last two decades. However, contrary to usual testing methods for which point-wise measurement of homogeneous stress and strain states, these techniques require that the mathematical expression of the constitutive relation is postulated. As a consequence, both workflows need to be implemented: 1.0 usual material testing for elaborating constitutive equations and estimating a first set of their parameters, 2.0 optimization of these estimates using full-field measurements and an inverse method [2] during an experiment in which a large variety of complex material states are explored.

Recently, the data-driven identification (DDI) [3] paradigm came with the potential of making 1.0+2.0=3.0. Starting from strain field measurements and their corresponding load measurements, DDI is aimed at estimating balanced stress field and a discrete clouds of points sampling the material response in a chosen constitutive space (e.g. stress-strain, or stress-strain-strain-rate,…). Doing so, complex mechanical test can be explored without postulating the mathematical expression of the material response. Promising results were obtained on a few cases: hyper-elastic materials [4], small strain (rate-dependent) plasticity [5],…

Considering the limitations of material testing 1.0 when necking and then ductile failure occur and the difficulty of constitutive modelling and numerical simulations in these case of scenarios, DDI becomes even more interesting. Developing DDI up to these extreme loading cases is the purpose of the proposed PhD thesis project. The goal is thus to extended the DDI formalism over its current limitations: finite strain, strain localization, softening material response, 3D deformation state… until it can be applied to ductile failure experiment on a 316L stainless steel [5].

The scope of the thesis thus encompasses those of non-linear mechanics, experimental mechanics, DIC and DDI. The project will be conducted within a collaboration between CEA and Centrale Nantes which are prominent in computational and experimental mechanics, applied mathematics, software engineering and noisy signal processing.

References

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[2] Pierron, F., & Grédiac, M. (2021). Towards Material Testing 2.0. A review of test design for identification of constitutive parameters from full-field measurements. *Strain*, *57* (1), e12370.

[3] Leygue, A., Seghir, R., Réthoré, J., Coret, M., Verron, E., & Stainier, L. (2019). Non-parametric material state field extraction from full field measurements. *Computational Mechanics*, *64*(2), 501-509.

[4] Dalémat, M, et al. "Measuring stress field without constitutive equation." Mechanics of Materials 136 (2019): 103087.

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Work description

Provisional Plan

During the first six months of the PhD, the candidate will acquire all the theoretical skills related to digital image correlation, inverse data-driven approaches, and the issue of ductile fracture in metals. The following three to six months will be dedicated to extending the method to a large transformation formalism, 3D deformation, softening response, and its numerical validation.

Over the next 12 months, the candidate will conduct a series of experiments, characterize the response using the developed tools, compare the results with existing models, publish their findings, and present their work at international conferences. Depending on progress, the final year will focus on high-performance computing (HPC) aspects and the writing of the PhD manuscript.

Techniques to be Implemented

The project includes the development of numerical tools, preferably adapted to HPC computing, the execution of experiments, kinematic field measurements using stereo image correlation, and material characterization.

Expected Outcomes

The research work should result in:

- ✓ The development of an efficient numerical tool capable of identifying stress fields in the context of ductile fracture in steel ;

- ✓ The experimental proof of concept based on kinematic measurements using stereo-correlation and the comparison of results with models from the literature ;
- ✓ The publication of at least one scientific article in a high-ranking journal (A-tier), the presentation of the research at multiple international conferences, and the completion of a PhD thesis manuscript.

Desired Candidate Profile

The candidate must have:

- ✓ A Master's degree (or equivalent) in engineering or mechanics (Bac+5) ;
- ✓ Strong knowledge in solid mechanics, continuum mechanics, and finite element methods ; Knowledge of DIC (Digital Image Correlation) and fracture mechanics would be a plus ;
- ✓ A strong interest in programming, particularly in Python ;
- ✓ A keen interest in both numerical and experimental mechanics ;
- ✓ Scientific rigor and curiosity ;
- ✓ Good written and oral proficiency in English.

Funding

This PhD thesis is fully funded by CEA.

Salary: 2406€ gross per month

A 35-hour, 3-year, full time contract from 01/10/2025 to 30/09/2028 (indicative period)

Supervision

Main supervisor : Julien Réthoré, Directeur de Recherche CNRS, GeM, Nantes

Centrale Nantes advisor : Rian Seghir, Chargé de Recherche CNRS, GeM, Nantes

CEA advisor : Pascal Bouda, CEA

CEA advisor : Duc Khai Nguyen Pham, CEA

Localisation du poste

The PhD will include a period of 12 to 18 months at GeM (UMR 6183), École Centrale de Nantes, followed by a period of 18 to 24 months at the CEA site (Paris-Saclay).

Contacts

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