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Environmental Fatigue Analysis of nuclear components within the framework of INCEFA-SCALE project

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Abstract

INCENFA-SCALE is a five-year project funded by the EC Horizon2020 programme, successor of the INCEFA-PLUS project. INCEFA-SCALE started in October 2020. The objective of this project is to improve the capacity to predict the lifetime of Nuclear Power Plant (NPP) components subjected to environmental assisted fatigue. The project starts off by analysing the existing data and then provides new environmentally assisted fatigue data which allow the laboratory test outcomes to be applied to components with real geometries and loads. So far, the data mining of different finished projects (INCEFA-PLUS, USNRC, EPRI, MHI and AdFaM) has been carried out, and test conditions for filling the knowledge gaps have been established. Moreover, the test matrix for 2022 has been defined. In this first phase, tests are focused on producing reference data, analysing complex waveforms (variable amplitude) and the effect of the surface finish. The next testing phases will focus on particular conditions: multi-axial tests, notches, stress/strain gradient effect and size effect. Furthermore, the microstructural analysis of common materials and a guideline for fatigue striation measurement on the fracture surface have been developed. This article provides an update on the project status and the advances made in data analysis, mechanical understanding and testing conditions.

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1. Introduction

INCEFA-SCALE is a five-year project funded by the Horizon 2020 program of the European Commission. This project is the successor to INCEFA-PUS, a project developed between 2015 and 2020. INCEFA-SCALE began in October 2020 and its objective is to continue the study of environmental-assisted fatigue (EAF), making progress in the capacity to predict the lifetime of components in nuclear power plants affected by this phenomenon.

Nuclear power plant operators have observed that failures attributable to EAF are fewer than those estimated by the calculation methods used so far (Tice et al. (2018)). One possible cause of this discrepancy is the transfer of laboratory test results to real-scale components. Additionally, the ability to address transferability between laboratory and component scales, both in geometry and loads, remains limited by data availability. This knowledge gap is addressed by INCEFA-SCALE. The plan of the project is, on the one hand, to further the knowledge of the mechanical behaviour through the exhaustive analysis of tested specimens and data mining, and, on the other hand, to perform tests which are focused on specific aspects of the loading conditions.

At present, the project is analyzing a large amount of previous test data collected in the MatDB database, managed by the JRC, from the INCEFA-PLUS project (INCEFA-PLUS Consortium (2020)) and other sources, such as USNRC, EPRI, MHI and the AdFaM project. The testing program has been defined and will be developed over the next three years. In addition, a series of protocols have been agreed: management of experimental data, testing protocol and analysis of the tested specimens. Finally, the project will generate a guide to apply the data obtained from laboratory to real-scale components.

Nomenclature

AdFaM	Advance Fatigue Methodologies Project
EAF	Environmentally Assisted Fatigue
FAP	Fatigue Assessment Procedure
FEA	Finite Element Analysis
MatDB	Online Materials Database
MHI	Mitsubishi Heavy Industries
NNL	Naval Nuclear Laboratory
NPP	Nuclear Power Plant
NRA	Nuclear Regulation Authority
PWR	Pressurised Water Reactor
SEM	Scanning Electron Microscopy
USNRC	US Nuclear Regulatory Commission
WP	Work Package

2. Objectives

The INCEFA-SCALE project aims to delve into the knowledge of the mechanisms involved in environmental assisted fatigue, improving the application of the laboratory tests data to the real loading conditions of components in nuclear power plants. The knowledge gap in predicting the fatigue life has been internationally recognised and it is of great importance. This is why EPRI is carrying out a series of component-scale EAF tests (Steininger et al. (2017)) to add to the amount of data available. It is hoped that these tests will improve the availability of data under component conditions, so that they can be related to laboratory data.

The strategy of INCEFA-SCALE is:

1. Develop a deep understanding of the mechanical behaviour by an extensive characterization of specimens tested under EAF conditions, together with a detailed data mining.

2. Undertake a test program focused on characteristic aspects of cyclic loads on real components.

Finally, the project will provide a guide to apply the data obtained in the laboratory to real loading conditions and components.

3. Background

Austenitic stainless steels are the chosen material for many of the cooling pipes in the primary circuit of pressurized water reactors (PWR) in nuclear power plants. They are exposed to high temperature and pressure, as well as chemically conditioned cooling water. These materials undergo non-uniform dynamic loading conditions.

Design codes ASME (2021) and experimental methods are used to estimate the fatigue life of components using simplified data, providing an environmental factor and, finally, defining the accumulated fatigue damage (Chopra and Stevens (2018)). Comparisons of these methods with tests performed on real-scale components suggest that these factors may be conservative, probably due to the transfer of laboratory data to real loads and components. The transferability of these results to the component scale behaviour in plant continues to be an area of interest and of insufficient knowledge, as Tice et al. (2018) highlight.

Recently, different studies by Currie et al. (2018) have provided a better prediction of the fatigue life of stainless steel specimens under thermal transients, or have defined the influence of the components surface finishing on fatigue life, by McLennan et al. (2020). Hence, conservatism may be reduced, reproducing more accurately the real working conditions. However, it is still necessary to increase the knowledge about the behaviour of stainless steels subjected to EAF and to advance in the transferability of laboratory data to components. The INCEFA-SCALE project addresses this issue.

The predecessor of INCEFA-SCALE, the INCEFA-PLUS project, evaluated the effect of the following factors on the fatigue life of austenitic steels: strain range, environment, surface roughness, average strain, strain rate and hold times, as well as their interactions. More than 250 tests were carried out in air and in a PWR simulated environment. As an important result of this project, by Bruchhausen et al. (2021), an experimental model was described, which identified strain range, environment and surface roughness as significant factors, as well as statistically significant interactions between environment and surface roughness, and environment and strain range. No effect of average strain or hold times was observed.

4. Project organisation

The project is composed of six work packages: WP1: Project Management; WP2: Data Mining; WP3: Test Program; WP4: Modeling and Developing Assessment Rules; WP5: Mechanical understanding; and WP6: Dissemination and Training.

The INCEFA-SCALE project consortium comprises seventeen organizations: Jacobs (UK, project coordinator), PSI (Switzerland), UJV Rez (Czech Republic), VTT (Finland), CIEMAT (Spain), IRSN (France), University of Cantabria (Spain), CEA (France), JRC (the Netherlands), Framatome (France), EDF (France), Inesco Ingenieros (Spain), Rolls-Royce (UK), Framatome GmbH (Germany), Technological University of Kaunas (Lithuania), KAERI (South Korea), and University of Manchester (UK).

The good cooperation and communication between partners, which characterised the INCEFA-PLUS project, is a key aspect in developing INCEFA-SCALE, since there is a close interdependence between the activities of data mining, testing, modeling and mechanical understanding.

Another characteristic of INCEFA-SCALE is its relationship with external organisations (USNRC, EPRI, MHI, NRA and NNL). These collaborations aim to guarantee the maximum relevance for the project results.

5. Project details

Most of the tests will be carried out on a common plant material, 316L stainless steel, supplied by EDF. In addition, some partners will test a specific 300 series stainless steel for their own national interest. This will make it possible to study the differences between the previous material tested in the INCEFA-PLUS project (304L) and the new material to be characterised.

Following the practice developed in INCEFA-PLUS, the participants will organise themselves into committees to define common testing methods and protocols. In addition, there is a committee, the Experts Panel, which will review the generated results to define its quality. Finally, all the organisations remain committed to agreeing on a common data format, as far as possible, since INCEFA-SACALE will have different test methods, as well as publishing the data in the MatDB repository, managed by the JRC. As a result of this commitment, four common procedures have already been agreed upon for all organisations: data management plan, testing protocol, procedure for the evaluation of the striation spacing, and procedure for open access publication.

5.1. Data mining

The analysis of data from prior test campaigns has been completed. The sources of these data were: INCEFA-PLUS project, different materials from national programs and MHI (all of them available in the MatDB database), in addition to data from VTT, USNRC, ANL and EPRI. These data come from both fatigue tests in air and in PWR environment. Fig. 1 shows a selection of fatigue test data in PWR conditions from the different sources.

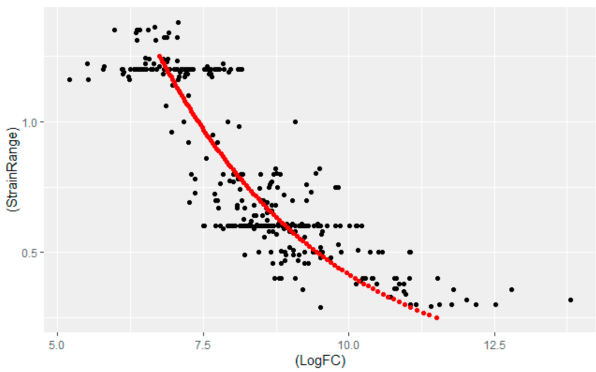

Fig. 1. Selection of fatigue test data in a PWR environment (in red, theoretical model).

From the analysis carried out, a lack of data at low strains and an effect of the cycle waveform on the fatigue life have been identified.

5.2. Test campaign

In addition to the uniaxial tests performed on solid and hollow cylindrical specimens, this project will cover additional test methods, such as membrane type specimens, the use of biaxial loads, notched specimens in uniaxial tests, or complex waveform tests. The objective is to explore particular responses which differentiate the EAF outcomes between laboratory tests and real components. The specific composition of the tests has been defined in WP3:

- WP3.3: tests with standard specimen geometries (solid and hollow). These will study the effects of surface finish, variable amplitude loading, and PWR environment. These tests began in November 2021 and some results are shown in Fig. 2. Currently (June 2022), 20 uniaxial tests have been performed.

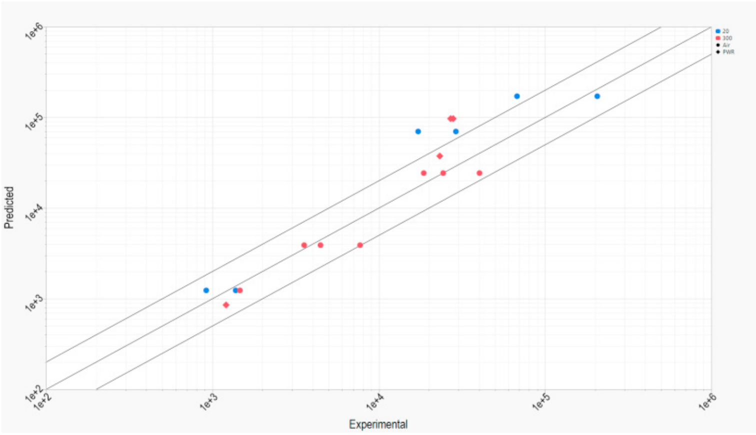

Fig. 2. First results from uniaxial tests.

- WP3.4: tests with non-standard specimens. These will study the effect of the loading conditions on the fatigue life through particularities incorporated into the design of the specimen, both in air and in PWR. For example, membrane-type specimens in PWR environment, in Dhahri et al. (2018); cruciform, in Gill et al. (2021); and solid specimens with notches. Trials of this type of tests will begin in November 2022.

In this first phase, the tests are focussed on defining the effects of variable amplitude and surface finish on the fatigue life of 316L stainless steel. Variable amplitude tests present periodic overloads with respect to a baseline of constant amplitude cycles, as shown in Fig. 3.

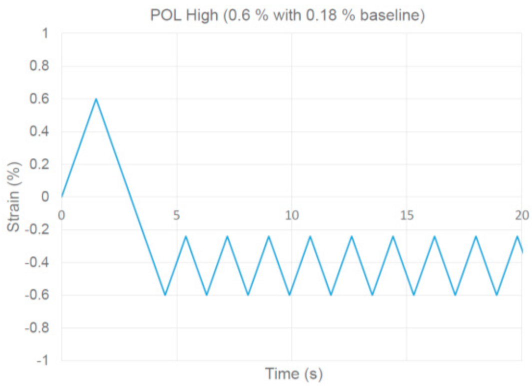

Fig. 3. Variable amplitude fatigue test.

The variety and complexity of the tests implies that it is necessary to avoid including more variables than those that can be analysed and are statistically relevant. On the other hand, since some of the methods that will be used are not standardised, it is important to understand how these results can be combined with those obtained in standardised tests. To mitigate these risks, an evaluation of the research topics was carried out, identifying their corresponding difficulty and potential benefits. In addition, an Expert Panel and an independent Advisory Board supervise and evaluate the tests of the project. These measures will keep under control the scope and quality of the tests.

6.3. Mechanical understanding

Usually, EAF assessments have been based on test results, simplifying experimental outcomes to develop fatigue curves and to estimate cumulative usage factors. One reason for these simplifications is the complexity and expensiveness of developing mechanistic models from experimental data. Although mechanistic models may not be widely acceptable from an engineering application perspective, they are required to support the use of simplified models in fatigue assessments and may lead to new approaches. Therefore, one objective of INCEFA-SCALE will be to advance in the development of mechanistic models for EAF, probably less conservative, and their application in engineering.

A better understanding of the EAF mechanism is essential. Since EAF is strongly affected by material conditions and load distributions, a microstructural analysis will be performed, along with finite element analysis (FEA). These activities will be carried out using commonly agreed methods for microstructural analysis. Within the framework of WP5, one of these procedures has been completed to evaluate the distance between fatigue striations (see Fig. 4, from Howe et al. (2022)). The characterisation will include the examination of specimens before and after testing. An attempt will be made to define the damage caused during the manufacture of the specimens and its evolution during the fatigue test. All this will provide information on relevant aspects of the fatigue mechanism, such as striation spacing or damage accumulation. The microstructural characterisation, in combination with the different types of fatigue tests, will improve the mechanistic understanding of characteristic NPP fatigue patterns.

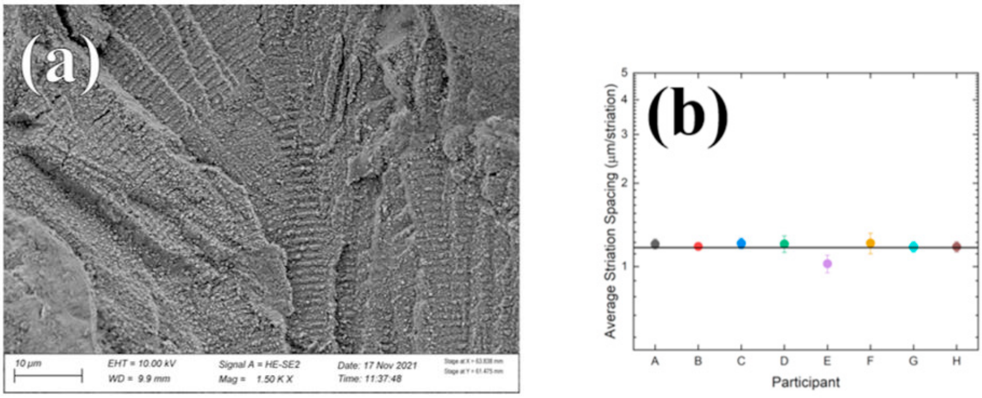

Fig. 4. SEM image of fatigue fracture surface. a) Analyzed area with fatigue striations; b) Measurements by different laboratories.

The definition and development of an INCEFA-SCALE evaluation model will begin at the end of 2022. While INCEFA-SCALE advances towards the standardisation of fatigue tests, the results will continue to be evaluated according to the current fatigue regulations, although without forgetting about the evidence and mechanistic understanding achieved so far. Building on the experience of INCEFA-PLUS, as shown in Vankeerberghen et al. (2018), the partners will analyse their data individually at first. During the previous project, this was an excellent method to ensure the creativity of the analysis. Afterwards, the members of the Expert Panel will meet periodically to discuss the ideas and come up with a uniform set of conclusions. From the data generated in the INCEFA-PLUS and INCEFA-SCALE projects, together with the incorporation of external data, new S-N curves (stress versus number of cycles) will be developed for different conditions. Mechanistic understanding will include the effect of environmental factors. The final purpose is to take an important step forward in evaluating the fatigue of nuclear power plant components under real conditions. To do this, the results obtained in INCEFA-SCALE will be used to develop a Fatigue Assessment Procedure (FAP).

6. Fatigue Assessment Procedure

At the end of the project, all the knowledge obtained will allow us to develop an environmental assisted fatigue life evaluation procedure, which will include the following information:

- Parameters that affect the aging of components in comparison with the specimens used in laboratories.
- Fatigue curves from the experimental program and the analysis of existing data.
- Equations that include the different parameters analysed and expressions of the environmental factor.
- Methodology for the fatigue assessment.
- Lessons learned report.

It is intended to write a document that could supplement current international design standards. The FAP will be applied to an industrial component to compare its result to those obtained from current approaches. An example of what to expect can be found in the equivalent open access document from the INCEFA-PLUS project, by Tice et al. (2018).

6. Project status

Since its beginning in October 2020, many virtual meetings of different subgroups with interests in mechanistic understanding, testing tasks, analysis of existing data and modeling have been held. The achievements so far (June 2022) have been:

- Collaboration with EPRI, under a confidentiality agreement (under development).
- WP2 has completed the development of a software that will facilitate data mining activities, using the information uploaded in MatDB. Additionally, external data will be available for reviewing (EPRI, USNRC and NRA).
- Members of WP3, WP4 and WP5 have shared ideas on the objectives of the respective WPs and the study priority.
- Uniaxial tests belonging to WP3 have started, with the support of the Expert Panel.
- Tests in featured conditions of the WP3 are being defined by a working group.
- The modeling and evaluation contained in WP4 has been started and its scope has been defined.
- The characterisation work of WP5 continues. A collaboration for counting fatigue striations has been completed and a common method for calculating the striation spacing has been defined. A subgroup of this WP is in the process of analysing the common material in untested samples.
- Dissemination and communication activities through scientific and professional forums, and publication of initial scientific documents.

7. Summary

The INCEFA-SCALE project has built on the successful results of the INCEFA-PLUS project. Frequent virtual and in-person meetings are being held in order to plan and manage the development of the different work packages, as well as to follow the evolution of the experimental campaign. Existing data analysis tasks have been carried out and the research needed to improve the knowledge of the mechanical behaviour has been defined. Specimen manufacturing, distribution to partners and testing are in progress. Collaborations have been established with EPRI and NNL (pending ratification) for component-scale testing.

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