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Procedia Structural Integrity 13 (2018) 97–103

Structural Integrity Procedia

www.elsevier.com/locate/procedia

ECF22 - Loading and Environmental effects on Structural Integrity

INCEFA-PLUS (Increasing safety in NPPs by covering gaps in environmental fatigue assessment)

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Abstract

INCEFA-PLUS is a European Project (funded by the EC HORIZON2020 program) started in July 2015 and lasts five years (until June 2020). The project involves 16 members from all over Europe and its main goal is to guarantee safety in operations of Nuclear Power Plants (NPPs) by delivering experimental data to support the development of improved environmental fatigue assessment guidelines. The issues of common interest are being studied: the effects of mean strain/stress, hold time, strain amplitude and surface finish on the fatigue performance of austenitic stainless steels in the LWR (Light Water Reactor) environment. Within the framework of the CEN (European Committee for Standardization) workshop FATEDA, the consortium developed a fatigue data format, used in an online environmental fatigue database, available for all participants. The paper describes phase one (of three) testing, including conditions such as surface finish and hold time. The plans that are being made for phase two testing will be detailed. The materials used in the tests, the surface finish data and some experimental results for phase one are presented, together with a summary of the INCEFA-PLUS testing protocol. Finally, a review of existing assessment methodologies and a summary of dissemination activities are provided.

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Peer-review under responsibility of the ECF22 organizers.

Keywords: Environmental Fatigue, INCEFA-PLUS, Light Water Reactor, Nuclear Power Plants.

1. Introduction

INCEFA-PLUS is a major five-year project supported by the European Commission HORIZON2020 program. The project commenced in mid-2015. Sixteen (16) organizations from across Europe have combined forces to deliver new

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Peer-review under responsibility of the ECF22 organizers.
10.1016/j.prostr.2018.12.017

experimental data which will support the development of improved guidelines for the assessment of environmental fatigue damage to ensure safe operation of nuclear power plants. The members of the project are:

- Studiecentrum voor Kernenergie - Centre d´Études Nucléaire (SCK-CEN) – Belgium
- Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT) – Spain
- Comissariat a l´Energie Atomique et aux Energies Alternatives (CEA) – France
- Electricité de France (EDF) – France
- European Commission, Joint Research Centre (JRC) – Netherlands
- Framatome – France
- INESCO – Spain
- Institut de Radioprotection et de Sûreté Nucléaire (IRSN) – France
- Lithuanian Energy Institute (LEI) – Lithuania
- Paul Scherrer Institute (PSI) – Switzerland
- PreussenElektra (PEL) – Germany
- Rolls-Royce – UK
- Teknologian Tutkimuskeskus (VTT) – Finland
- UJV-Rez – Czech Republic
- University of Cantabria (UC) – Spain
- Wood – UK

Prior to the start of INCEFA-PLUS, an in-kind study was undertaken by several European organizations with the aim of developing the current state-of-the-art for this technical area. In addition to stress/strain amplitude, this study identified three experimental sensitivities, which required further study in order to support an improved assessment methodology for environmental fatigue, namely the effects of mean stress/strain, hold time and surface finish. Within INCEFA-PLUS, the effects of these three sensitivities on the fatigue endurance of austenitic stainless steels in light water reactor environments are therefore being studied experimentally. The data obtained are being collected and standardized in an online environmental fatigue database. A dedicated CEN (European Committee for Standardization) workshop that finished at the end of 2017 was supported by the project. It had the aim to harmonize data formats and thus facilitate the exchange of data within the project but also beyond. As for now, access to the database is only available to the consortium, but agreements are currently being developed so that other organizations can have access to the data, in exchange for access to theirs.

Based on the data generated and the resulting improvement in understanding, INCEFA-PLUS is developing and disseminating methods for including the new data in assessment procedures for environmental fatigue degradation. This will better account for the effects of mean stress/strain, hold time and surface finish.

This paper describes the background and current status of the project as well as the expectations for the next few years.

Nomenclature

EAF	Environmental Assisted Fatigue
EPRI	Electric Power Research Institute
LWR	Light Water Reactor
NUGENIA	NUclear GENeration II and III Association

2. Project background

In recent years, a great deal of research work has been undertaken to address the influence of high temperature LWR coolant environments on the fatigue of pressure vessels. The Regulatory Guide 1.207 of the USNRC (United States Nuclear Regulatory Commission) (US-NRC (2007)), with a support report of ANL (Argonne National Laboratory), NUREG / CR-6909 (Chopra and Shack (2007)) and NUREG / CR-6909, revision 1 (Chopra and Stevens (2018)), deals with the influence of LWR environment on the fatigue life of reactor materials. It is clear that the effect of the cooling environment of light water reactors can reduce the resistance to fatigue compared to what is expected in the air. The application of the revised procedures may result in predictions of very high cumulative fatigue usage factors for some plant components, which seems to be inconsistent with the relatively good performance of stainless steel components in operating reactors for several decades. Despite the extensive nature of the data that has been used to derive the relationships provided in the NUREG / CR-6909 report, there are a significant number of knowledge gaps. These gaps have been reviewed in a recent study, sponsored by EPRI (Tice et al. (2011)).

This review was updated in a European context in 2013 through a NUGENIA project, called INCEFA (Increased safety in nuclear power plants covering deficiencies in the assessment of environmental fatigue). The members of this project were:

- Amec Foster Wheeler - Wood – UK
- AREVA - Framatome – France
- Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT) – Spain
- Commissariat à l´Énergie Atomique et aux Énergies Alternatives (CEA) – France
- Electricité de France (EDF) – France
- EKK - PreussenElektra (PEL) – Germany
- European Commission, Joint Research Centre (JRC) – Netherlands
- INESCO – Spain
- Paul Scherrer Institute (PSI) – Switzerland
- SCK-CEN
- Teknologian Tutkimuskeskus (VTT) – Finland
- UJV-Rez – Czech Republic
- University of Cantabria (UC) – Spain

The result of this project was a European view of the state-of- the-art for the Environmentally Assisted Fatigue assessment capability. The current state of understanding on a significant number of issues affecting the accuracy of fatigue life prediction was discussed and areas where additional work was considered desirable were identified. In addition to the stress/strain amplitude and the LWR environment, three of these potential future research areas were of common interest to all parties:

- Effects of surface condition
- Effects of hold time
- Effects of mean stress/strain

Based on these conclusions, the European Commission, under the Horizon2020 framework program, has agreed to fund a new five-year program with the aim of further investigating those effects. The new project was named INCEFA-PLUS and its members are the same as those of the INCEFA project plus:

- Institut de Radioprotection et de Sûreté Nucléaire (IRSN) – France
- Lithuanian Energy Institute (LEI) – Lithuania
- Rolls-Royce – UK

The program is approximately 33% (~€2.5M) funded by the EC (European Commission) and the remaining funds come from national research programs.

3. The project organization

The INCEFA-PLUS project is divided into four work packages, as shown in Figure 1. The project is organized in 3 main parts: the first one deals with the tests and the experimental program; the second one analyzes the data generated in the tests and uses other existing methodologies to build a new fatigue methodology; and the third one is focused on the dissemination of the lessons learned during the project. The duration of the project is five years, starting in July 2015 and the tests are expected to take three years, starting in mid-2016. There are 16 members in the project and 13 of them are conducting tests. All of them are committed to testing all three highlighted sensitivities and to use the same agreed test protocol. Twelve laboratories have been performing tests on a 304L material, provided by EDF, so that the variations between these facilities can be quantified. Eleven of them have committed to performing air and water tests. All members of the project are engaged in supplying data in a common agreed format.

In LWR environment, tests have been performed both on solid and hollow specimens. A member of the project (EDF) provided a common material (AISI 304L) for several partners to test. In order to provide surface finishes that are as consistent as possible between laboratories, hollow specimens and both polished solid and rough solid specimens have been manufactured in the same facility. The non-common material (participants' own 300 series stainless steels) specimens have been characterized with the objective of understanding the surface finishes obtained (since they have been made for each participant in their own laboratory) and identify possible reasons for outlier results. Common material specimens have also been characterized.

The development of test matrices is being addressed with the Design of Experiment methodology (Bruchhausen et al. (2017)). This approach ensures that the program addresses interdependencies between sensitivities, whereby the sensitivity of fatigue endurance to one parameter can be affected by a variation in another.

The key deliverables of the project include a protocol for EAF testing (that could form the basis to a future ISO standard), new fatigue curves, new or modified fatigue analysis procedures, and a reference book suitable for possible conversion to an assessment standard, among others.

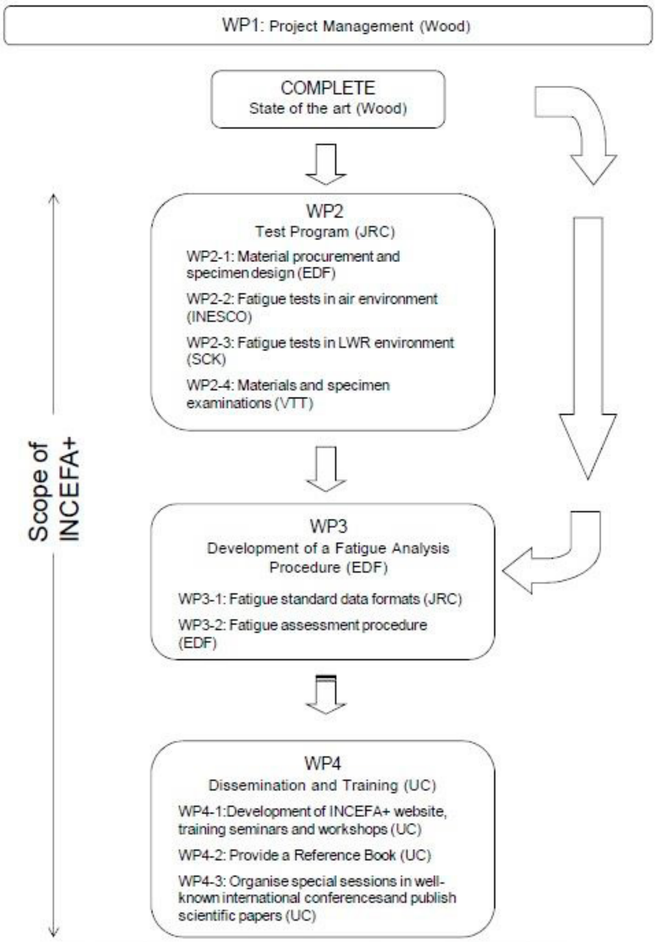

Fig. 1. INCEFA-PLUS organizational flow chart

4. The tests

The INCEFA+ fatigue test programme involves subjecting a series of specimens to the number of strain cycles required for a fatigue crack to initiate and grow large enough to cause failure, or a pre-agreed load drop, during exposure to LWR environment and, for reference, to an air environment at two alternating strains (0.3% and 0.6%). The objective for both environments is to define the fatigue strength at N cycles, S_N, from a fatigue curve, and, hence, to determine the environmental correction factor F_{en}.

The INCEFA+ fatigue tests are used to determine the effect of surface roughness, strain amplitude, mean stress/strain and hold time on the corrosion fatigue life of 304 stainless steel subjected to an applied strain range (or occasionally stress range) for a relatively low numbers of cycles (low cycle fatigue).

4.1. Hold time and mean stress/strain

Specification of conditions for hold time and stress/strain was particularly demanding. Some considerations about these issues will be made next.

Whereas conventional fatigue testing usually applies continuous triangular or sawtooth cyclic loading, this does not represent power plant operation (in which long periods at relatively constant load are alternated with occasional larger transients). The aim of the hold time tests is therefore to assess the extent to which the fatigue lives measured in standard cyclic fatigue tests are relevant to plant conditions.

The proposed plan for hold time testing for INCFA-PLUS is to perform the tests at a temperature of 300ºC, with strain amplitudes of 0.3% and 0.6%, using a waveform of sawtooth (with faster load drop to help test efficiency). This way, the project can address conflicting data in open literature and perform tests that consider plant relevant holds in a manageable test duration. The planned hold frequency (with a maximum of 3 holds per test) is shown in Table 1:

Table 1. Planned hold frequency

Number of cycles	Air/LWR	Strain amplitude (%)
Every 6000 cycles	Air	0.3
Every 1200 cycles	LWR	0.3
Every 1000 cycles	Air	0.6
Every 200 cycles	LWR	0.6

The majority of INCEFA+ fatigue tests is performed under strain control with mean strain for Phase I testing. Strain amplitude values of 0.3% and 0.6% were planned, with either zero or 0.5% mean strain during cycling, Table 2.

Table 2. Mean strain

ε_a (%)	Mean ε (%) for cycling	ε range (%)	Hold ε (%)
0.6	0	-0.6 to 0.6	0
0.6	0.5	-0.1 to 1.1	0.5
0.3	0	-0.3 to 0.3	0
0.3	0.5	0.2 to 0.8	0.5

No effect of mean strain has been seen in the strain control tests (0.5% mean strain was applied). This result was anticipated and provides a useful comparison against already available data for similar tests in strain control. Exploration of mean stress effects under both strain and stress control is carried out in parallel to the main Phase 2 testing.

4.2. Phases of the project

The project has three testing phases: phase 1 started in December 2016, phase 2 in May 2018 and Phase 3 is being defined. At the time of writing this paper, 56 (of 74) tests have been performed. The remaining tests are expected to be finished by August 2018. Sixty-five (65) of them are on a common 304L structural material relevant to current European nuclear power plants.

The tests have been performed in accordance with a “Test Protocol” (Vankeerberghen et al. (2018)), developed by the consortium, that determines the specimen size, the temperature, humidity level and pressures during the tests and the procedures to identify and store the specimens, among others. An expert panel has been created with the aim of reviewing all data generated by the project to ensure high data quality.

So far, there is insufficient data to reveal any effect of hold time; so, further tests will be performed in Phase 2 to confirm this information. No effect of mean strain (0,5% mean strain has been applied) in strain control tests have been observed, which is consistent with literature. Additionally, for the time being there has not been any significant variability between laboratories performing the same kind of tests.

The quality of the data generated in Phase 1 testing is quantified and taken into account by a series of actions, such as the formation of the expert panel (previously mentioned), the agreement to criteria to quantify completeness and quality of data (Vankeerberghen et al. (2018)) and use of a standard data format for exchanging test data between laboratories.

The project is currently in Phase 2 testing which includes roughly the same number of tests as Phase 1 (74). The main differences with respect to Phase 1 are: no further strain control tests with mean strain will be performed, since there are enough data for this condition and no effects were found in phase 1 which is consistent with expectations. Higher strain rates will be used for tests in air, to reduce the test time; rougher surface finishes (in some ground surface specimens) will be used to explore this condition in more detail. Besides, some tests (8 to 10) will be dedicated to studying mean stress effect in both strain and stress control tests, with a view to highlighting possible sensitivities in both air and LWR environments.

At the time of writing, intensive analysis of the data generated within the project has not yet started as the fatigue database needs to reach a certain size to allow running reliable statistical analyses, and should also provide a well-balanced representation of the different studied parameters (in terms of sub-populations size). The database is only populated with data points that have been assessed by the project expert panel in order to include quality as part of the analysis, and the critical size is expected to be reached by the last quarter of 2018. The fatigue assessment procedure development will then begin at that time.

First thoughts on the direction the project is taking in terms of a fatigue model can be summarised as follows. In order to stay in line with already codified approaches or regulatory guidance documents based on the environmental F_{en} factor, the fatigue assessment procedure will be developed for the next two years by reinvestigating each step of these approaches (for which over-conservatisms have already been identified in the literature), especially with respects to the three effects (surface finish, mean loads, hold times) that are being studied within the project. An impact is expected at least on the design air curve (transference factors on life and strain amplitude) and on the F_{en} factor (its mathematical expression or its implementation in usage factor calculation).

5. Dissemination

One of the four Work Packages of the project is focused on dissemination and training. It manages, among other things, creating a website for the project (www.incefaplus.unican.es) and running seminars. The first took place in Santander, Spain, in June 2018 and its main goal was to introduce fatigue and environmental fatigue phenomena. The second one is expected to occur in mid-2020, by the end of the project and it is expected that the project findings will be published then.

Another important commitment made by the consortium and that was a requirement for EC was to organize special sessions in well-known international conferences and publish scientific papers. Many papers have been published already, many are yet to be published, and special sessions have been organized in two international conferences: ICMFM 18 (Gijón, Spain, September 2016) and ASME PVP 2018 (Prague, Czech Republic, July 2018).

Finally, a Reference Book will be provided with a summary of the data, the developed fatigue assessment procedure, the results and the conclusions of INCEFA-PLUS

6. Conclusions

The main goal of the INCEFA-PLUS project is to cover some gaps in environmental fatigue assessment and for that purpose, studies and tests are being performed. Some first results have been analyzed and preliminary conclusions have been drawn (for example: no effect of mean strain on strain control tests has been observed) for Phase 1. A more thorough analysis will be carried out once all the data are available.

Acknowledgements

This project has received funding from the Euratom research and training program 2014-2018 under grant agreement No 662320.

The contributions of all partners in the INCEFA-PLUS project are also acknowledged.

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