Mid-term workshop

19-20 September 2023

Santander, Spain

Building an international fatigue project: successes of INCEFA+

Kevin Mottershead

This project has received funding from the Euratom Research & Training programme 2019-2020 under grant agreement N° 945300.

Contents:

1. Brief history
2. Strategies to build success
3. INCEFA+ outcomes
4. Conclusion

1. Brief History

- Widespread worldwide concern about new NUREG/CR-6909 rules and their impact on EAF lifetime assessments for PWR plant. Belief was widely held that the rules introduced conservatisms, some of which were already included in already established design fatigue curves. But available historical data couldn't quantify this reliably enough.

- University of Santander launched the idea of combining laboratory EAF testing in Europe to achieve greater statistical weight to justify reducing NUREG/CR-6909 conservatisms, project name INCEFA proposed.

2012 **2013** **2015** **2020**

1. Brief History

- Due to staff changes in UC, Jacobs (Amec at that time) took on leadership role for INCEFA, first gathering of interested parties took place in Budapest in March 2013.
- Agreed to collaborate on in-kind basis initially to develop a State of the Art position.
- Meanwhile, in parallel to pursue EC funding for a five year testing project.

2012 **2013** **2015** **2020**

1. Brief History

- EC funded 5 year project commenced, named INCEFA+ to differentiate it from the in-kind work done before.
- Project objectives were to investigate sensitivities of EAF lifetimes to environment, surface finish, hold times and mean stress, and if justifiable, propose alternative ways of allowing for these effects in lifetime assessments.

2012 **2013** **2015** **2020**

1. Brief History

- INCEFA+ concludes having made significant advances in supporting EAF lifetime assessments, and also attracting significant international interest.
- Follow-on, EC funded, project INCEFA-SCALE commenced, aimed at tackling uncertainties regarding translation of laboratory scale test data to full scale plant components.
- Notable that INCEFA-SCALE now includes new European participants, plus participation from outside Europe from South Korea and the USA.

2012 **2013** **2015** **2020**

2. Strategies to build success

Three aspects to the Strategies:

- Statistical Significance
- Reliability of Assessment Curves
- Common Focus

2.1 Strategies to build success: Statistical Significance

Historical EAF data has significant variation in experimental practices - wide scatter bands when data is combined for S-N curves.

To challenge conservatisms we must minimise new data scatter. This was (and still is) tackled in five ways.

- Common materials:
- Common specimen machining:
- Common test machine setups:
- Common testing methods:
- Expert panel

2.1 Strategies to build success: Statistical Significance

Common materials:

- As a minimum participants committed to all include some tests on a common heat of plant relevant material, many participants used their national funds to test the same material as well.
- When national interests dictated testing on non-common material, the participants committed to supplying full material properties so as to enable better quantification of material sensitivities.

2.1 Strategies to build success: Statistical Significance

Common specimen machining:

- Surface finish was a sensitivity to be studied, hence important for specimens to be manufactured consistently.
- Agreed to have all common material specimens machined in one location, with fully documented machining parameters.
- National material specimens would be machined locally but effort was made to adhere closely to the common material machining parameters; local machining also well recorded to help explore machining induced sensitivities.

2.1 Strategies to build success: Statistical Significance

Common test machine setups:

- All helped develop a test protocol to which we would all adhere.
- Objective was to minimise laboratory induced scatter in results.
- Protocol stipulated requirements including:
  - test machine alignment
  - control and instrumentation set up and calibration
  - test specimen environmental control
  - laboratory environmental control
  - care of test specimens.

2.1 Strategies to build success: Statistical Significance

Common testing methods:

- Protocol also prescribed how testing should be performed (e.g how to start and finish tests), and the data to be recorded and monitored during tests.
- Protocol also ensured everybody was working to a common understanding of how a test is specified (e.g common understanding of N_{25}).

2.1 Strategies to build success: Statistical Significance

Expert panel:

- Participants agreed to formation of panel of experts who would review and challenge all experimental data, and conclude by awarding quality ranking which would be filed with each data point.
- Common reporting template developed so that the data was presented to the panel consistently.
- Panel used data and hysteresis loops to ascertain data reliability.
- Panel members often helped laboratories tackle any problems highlighted by Expert Panel review.

2.2 Strategies to build success: Reliability of Assessment Curves

Three approaches:

- Common Database
- Robust Data Assessments
- International Fatigue Database

2.2 Strategies to build success: Reliability of Assessment Curves

Common Database:

- Agreed from the outset to compile all data into the JRC MatDB database.
- As well as encouraging common data formats, this also ensured all data assessment activities would use a common source of data.

2.2 Strategies to build success: Reliability of Assessment Curves

Robust Data Assessments

- Body of data modelling expertise was convened
- Each member worked initially alone reviewing and analyzing the data.
- Analysis methods compared and further developed.
- Result was findings backed up by independent analyses.

2.2 Strategies to build success: Reliability of Assessment Curves

International Fatigue Database

- Through project dissemination (e.g ASME PVP) international awareness of us increased.
- Thus the idea for adding to MatDB with data from outside the project (including historical data used for USNRC/CR-6909).
- Major challenges setting up agreements, finally overcome in 2023 in time for INCEFA-SCALE to benefit from data offered by:
  - NRA in Japan
  - USNRC
  - EPRI
  - and soon hopefully others who have expressed interest

2.3 Strategies to build success: Common Focus

Many European projects suffer from competing national interests which can dilute the collaboration focus.

- From outset consortium agreed to full project gatherings on six-monthly frequency. This started during the 2013-2015 in-kind phase and continues today.
- Face-to-face gatherings are favoured since they permit better exchange of views during inevitable technically challenging discussions. They help build teamwork and also helped us clarify technical direction early in the project (e.g. “mean stress” focus proved to be an enormous challenge that required much debate.)
- 6-month frequencies meant reduced time for national pressures to deflect focus.
- Remote and airport meetings also used when momentum needed to be maintained between 6-monthly meetings (e.g Expert Panel meetings, meetings to address testing or assessment challenges).
- Off course COVID impacted this. However, it is testament to the developed teamwork of the consortium that the impact was small. Post-COVID emphasis is once more face-to-face meetings plus remote or airport meetings as necessary.

3 INCEFA+ Outcomes

~250 results created over 3 one year phases

- Phase 1: surface finish, hold time, mean strain and environment varied, F_{en} 4.57 for PWR tests.
- Phase 2: extra surface finish effect studied instead of mean strain (no mean strain effect confirmed). Small mean stress test program started.
- Phase 3: hold time tests refocused to examine reasons for no sensitivity when historical data showed sensitivity. Mean stress program continued. Reduced F_{en} 2.68 tests introduced to test for sensitivity of surface finish results to F_{en}

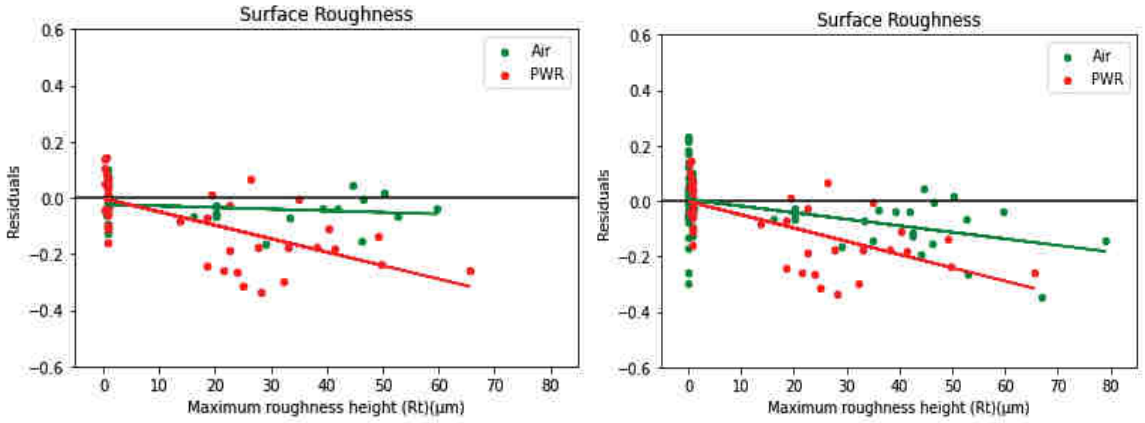
Independent analyses done to confirm data sensitivities

Analyses done to quantify laboratory and specimen induced data variance

Statistical analysis used to translate results into implications for plant fatigue assessments

3 INCEFA+ Outcomes: Data Sensitivities

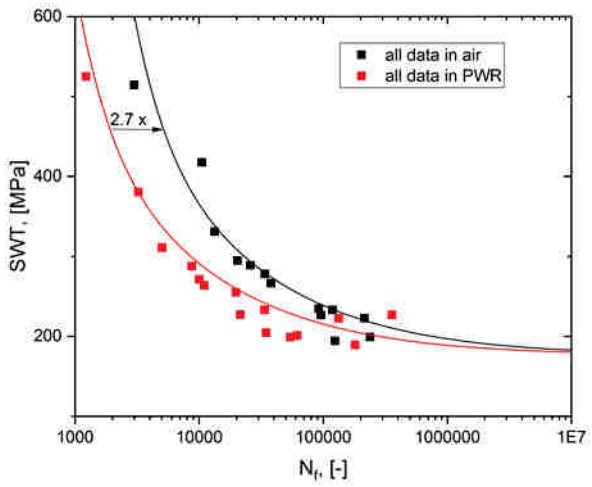
- Only significant sensitivity is to surface finish, environment and strain amplitude.
- No sensitivity apparent to either mean strain or hold time.
  - Mean strain was confirmatory
  - Hold time insensitivity was surprising given historical data demonstrating possible benefit. Further work has established that very particular circumstances are needed to realize hold time benefits.
  - Previously seen differences between surface finish effects in air and PWR not reproduced, though deleterious effect of surface finish is, in both environments (some suggestion of a strain amplitude sensitivity for surface finish effect). Surface finish sensitivities in PWR are consistent with those assumed by FEN-threshold type methodologies



Plots show residuals in air and PWR for results compared to predictions based on material best fit curve plus CR-6909 F_{en} (left image excludes additional French data, right includes it)

3 INCEFA+ Outcomes: Data Sensitivities

- Smith-Watson-Topper (SWT) method used to combine results for mean stress testing under strain or stress control.
- SWT developed into $F(N_f)$ using empirical $\sigma_{max}/\varepsilon_a$ relationship, plus NUREG CR-6909 mean curve for N_f/ε_a & F_{en} factors.
  - Results confirm that NUREG CR-6909 F_{en} is not affected by mean stress application under strain or stress control (for the conditions tested; ~0.2% ε_a)
  - SWT parameter demonstrated useful for consideration of complex load scenarios, possibly useful for INCEFA-SCALE.



3 INCEFA+ Outcomes: Lab & Specimen Variance

- Hollow specimen data from 3 labs compared, also compared with solid specimen results.
- Variation between labs, and for different specimen diameters, assessed by analyzing solid specimen data.
- No systematic variability evident between labs, or by specimen diameter; factor 1.5 deduced for lab-lab variability (95% confidence).
- Hollow specimen data for two labs is consistent and shows consistently lower lives than for equivalent solid specimen tests, 3rd lab's hollow data demonstrates lives closer to equivalent solid specimen results.
  - FEA modelling, plus detailed comparison of test methods unable to explain observed variance.
  - Sensitivity study used to show that INCEFA+ results are insensitive to the variances; attributed to specific test matrix composition and probably not generally applicable.

3 INCEFA+ Outcomes: Implications

- Statistical analyses employed have been complex; however, the result is simple.
- Surface finish sensitivity in PWR conditions, when compared with NUREG/CR-6909 guidance, supports the claiming of a margin of 3 on life when using 6909 rules.
- Results underpin already existing fatigue procedures incorporating this margin:
  - ASME Code Case proposal $F_{en\text{-}threshold}$ (USA)
  - AFCEN RCC-M $F_{en\text{-}integrated}$ (France)
  - $F_{en\text{-}incorporated}$ (UK)

4. Conclusions

International acclaim says it all!

- Our work has been able to underpin emergent European and American fatigue procedures.
- Our use of MatDB, testing protocols and Expert Panel reviews has been adopted as best practice by other EC supported projects.
- The IFDA looks like being more than a simple database which all signatories can access; there is a desire for the signatories to work together to ensure better outcomes for fatigue assessment methods. New applications to join the agreement are already appearing.
- We are now working extremely closely with USNRC (the custodians of USNRC/CR-6909) and EPRI (the leaders of a major full plant scale EAF test programme).

JACOBS

Thank you!

INCEFAscale
Horizon 2020

incefascale.unican.es

incefascale@unican.es

@IncefaScale

INCEFA-SCALE

INCEFA-SCALE H2020

This project has received funding from the Euratom Research & Training programme 2019-2020 under grant agreement Nº 945300.