SINDRI: Synergistic utilisation of INformatics and Data centRic Integrity engineering

Business Lead: EDF | University Lead: University of Bristol | Grant reference: EP/V038079/1

OBJECTIVES AND AIMS OF THE PROJECT

The Synergistic utilisation of INformatics and Data centRic Integrity engineering (SINDRI) Prosperity Partnership is developing digital tools, the SINDRI toolbox, that will initiate a step-change in the nuclear industry's design and in-service assessments of materials and components. SINDRI will use advanced predictive materials models, underwritten by high fidelity experiments, together with model reduction methods, to translate manual processes to a virtual environment which enables the application of robust probabilistic-based assessments.

SINDRI key objectives are: **1 -** Quantify the **effects of fabrication and in-service environment on materials microstructure** and its evolution using **high-fidelity experiments**. **2 -** Employ and develop **microstructurally informed, multi-physics models** to **simulate fabrication and in-service behaviour** of representative **alloy systems**. **3 -** Implement **data-driven methods** and approaches such as **model reduction**, data assimilation, and **uncertainty quantification** to enable **modelling activities to cross length scales**. **4 -** Provide the nuclear industry with a controlled and validated set of methods, the **SINDRI toolbox**, to enable a **robust probabilistic approach** distinct from the current expensive and conservative deterministic methods.

SUMMARY

The nuclear industry faces substantial challenges in delivering cost effective technical advancements which will impact its contribution to a net zero carbon economy by 2050. By building a comprehensive suite of integrated tools the project is striving to demonstrate a digitally connected route to reducing significant time-consuming and cumbersome human interventions enabling high throughput analysis with next generation digital tools.

Progress has continued at pace in the development of the project's central repository for its tools development - **SINDRI Toolbox** – a welding simulation tool is now integrated into the toolbox, and micromechanical modelling and ML tools are being finalised for integration. Critically, 2024 has seen this accompanied by the growth of EDF's team engaging with the toolbox. SINDRI now has a suite of modelling tools and experimental validation which span the grain to component level for material deformation. This validation has been delivered by access to state-of-the-art experimental capabilities and large-scale facilities at the Sir Henry Royce Institute ("Royce"). A major focus has been the development of data reduction/surrogate methods to act as the bridge between these digital tools – methods to account for texture and uniaxial deformation have been delivered and the challenge is now to translate these into a multiaxial framework for use in standard engineering tools such as finite element packages and to develop robust damage models, building on the exciting developments from this year.

Technical output from the academic partners in the form of papers and conference papers has continued to ramp up. Wider impact will come from industrial implementation, and EDF's main activities on the toolbox in 2024 have focussed on: independent testing of the weld residual stress module by a third party (DigiLab), initiating a migration of the academic repository to EDF's secure systems, and identifying follow-on studies to update EDF's structural integrity engineering guidelines, ensuring the toolbox's industrial applicability. To date, SINDRI has supported the life extension of the AGRs and the same approach is applicable to life extension of Sizewell B and maintains UK capability to support an HTGR demonstrator (a DESNZ priority).

DEVELOPMENT IN THE LAST 12 MONTHS

Some of the major achievements in 2024 have come from the **Meso-scale Modelling work package (WP1.2)**. A novel mesoscale crystal plasticity approach to predict creep damage initiation under multiaxial stress conditions has been developed to support improved prediction accuracy and cost-reduction in power plant life-time assessment. The model focuses on damage prediction for 316H austenitic stainless steel in demanding thermomechanical loading situations. The model predicts damage (Figure 1c) by first computing the deformation at mesoscale in a finite element domain (Figure 1b) and then, correlating microstructural variables such as maximum shear strain rate, $\dot{\gamma}_{max}$, and stresses with the experimentally measured damage (Figure 1a).

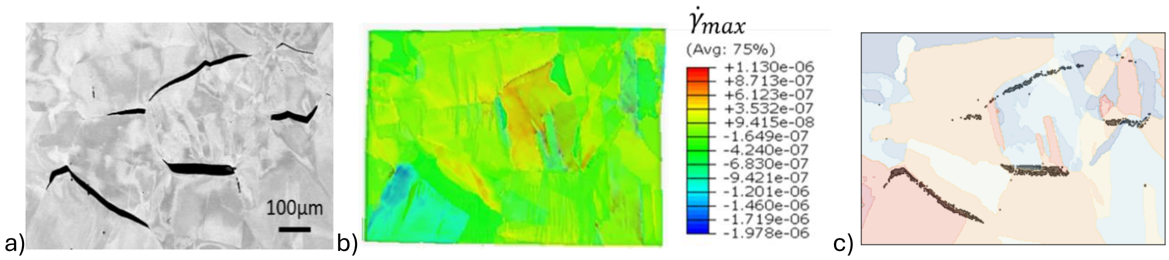


Figure 1. a) SEM image of creep damage b) Maximum shear strain rate, and c) Creep damage predicted by crystal plasticity model.

Validation data are critical for this modelling and WP1.1 has addressed the limitations of previous 2D microstructural analyses. To provide the models with detailed data on local grain orientation and damage development, a novel spatial approach using Royce 3D electron backscatter diffraction and secondary electron microscope, EBSD/SEM, and machine learning enabled image analysis has been developed to visualise the volumetric grain structure and distribution of creep cavities (*Figure 2*), enabling the correlation of microstructure and creep cavitation in a large representative volume.

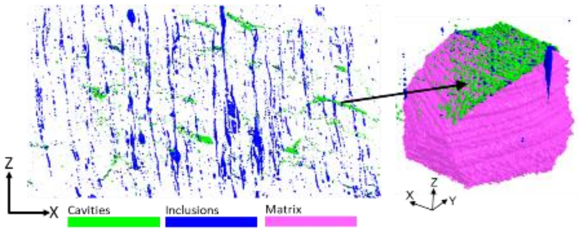


Figure 2. Distribution of inclusions and cavities after segmentation using a trained machine learning tool with correlation to grain morphology. Global loading direction is parallel to the Z-axis.

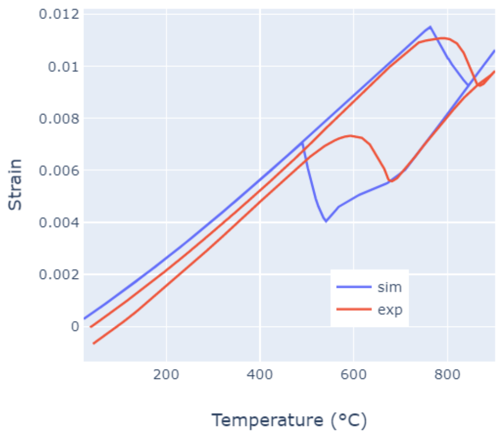


Figure 3. Fast-cooling dilation response of weld metal, red, showing discrepancy with existing predictive model, blue.

WP 2.1 – **Macro-scale Experiments** – continues to advance microstructure-informed continuum modelling of weldments. Low-alloy steel forgings are welded together to fabricate safety-critical components. Phase transformation validation through dilatometry testing and microstructural characterisation have been carried out, to evaluate non-equilibrium transformation behaviour associated with welding. These data are being used to extend existing analytical models. A comparison between experimental and simulated dilation curves is illustrated Figure 3. This will allow prediction of residual stress development in welds - a key element to support life extension of the Sizewell 'B" nuclear power station.

Surrogate model (WP 3.1) has seen major progress. The activity has delivered a particular novel surrogate model architecture based on the concept of neural operators (NOs) enabling the results of high-fidelity simulations, generated within WP1.2, at meso- scale to be used to simulate whole components as schematised in Figure 4. The NO surrogate model's unique architecture learns how to efficiently describe material behaviour in terms of a limited number of internal state variables and learns how these variables evolve with load history. This already enables physical effects such as kinematic hardening to be captured from meso-scale models and has the capability to capture damage in the future. Great progress has been made in ensuring these models plug into existing engineering finite element modelling tools such, e.g. ABAQUS. Work is on-going to with EDF to deploy the developed tools in the SINDRI toolbox (WP3.2).

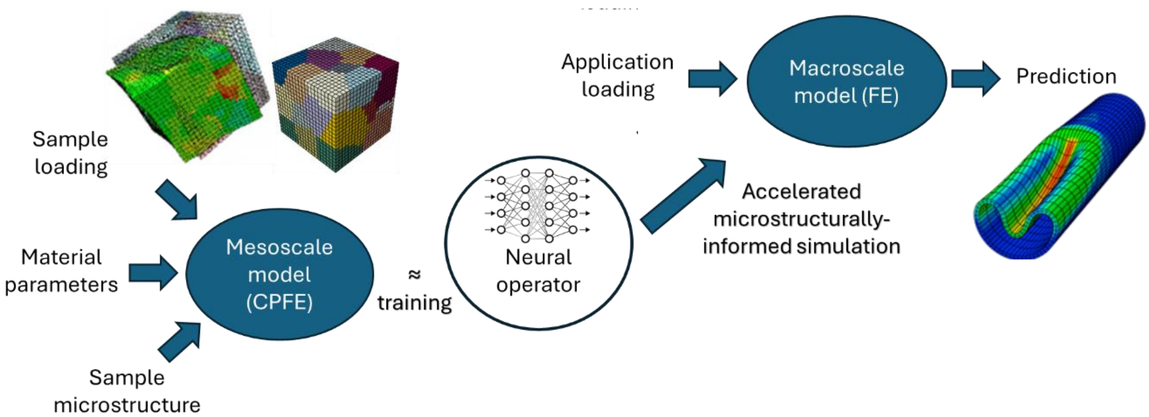


Figure 4. The proposed NO surrogate model for multiscale prediction of material state.

THE BUISNESS PERSPECTIVE

Nuclear energy must maintain and operate plant with long operating lifetimes to ensure commercial viability. This presents a number of key structural integrity challenges:

- Predicting how material properties will evolve and degrade in hostile environments, over long timescales (e.g. 40-60 years). Very long-term lab testing is not impractical and operating plant materials often represent the edge of current understanding.
- Using improved analysis to justify the extension of the safe operating life of plant, maintains generating capacity and so maintains revenue streams

The mechanistic models being developed as part of the SINDRI project support both of these industry challenges. The meso-scale models being developed offers the potential to predict how harsh environments and ageing alter material structure, and the resulting impact on bulk material properties and structural integrity. Longer term, there is huge potential for cost and time savings on material testing, as well as supporting robust probabilistic predictions where testing is impractical (i.e. very long timescales). SINDRI is developing an end-to-end ability to translate from material microstructure to component performance. The tools being developed into SINDRI Toolbox will help bridge the gap between research models and industrial applications.

Skills being developed and knowledge transferred across the various partner organisations also support the re-development of the UK nuclear supply chain which is critical to support future reactor plant operation.

COLLABORATION AND INTERACTION

In the last year, the SINDRI team have continued disseminating their work in national and international events, ensuring SINDRI visibility and impact.

- SINDRI Annual Conference hosted at Imperial College London on 24th of September. This event focuses on realigning the project with its aims and showcasing SINDRI's excellence in research. The day was filled with technical talks delivered by PhD students and PDRAs. EDF's representatives from EDF highlighted the wide industrial impact of digital tools.
- The team presented research outcomes internationally with 7 papers at the 2024 | PVP® Pressure Vessels & Piping Conference® | July 2024. , and *"Developing a reduced-order representation of crystallographic texture for application in surrogate modelling and uncertainty quantification of crystal plasticity models"* at the 5th International Symposium on Probabilistic Methodologies for Nuclear Applications | FESI in Tokyo, Japan.
- In February, the team was among the finalist at the Engineer's Collaborate to Innovate Finalist Ceremony at One Great George Street in central London. An opportunity to establish the success of the project at national level and showcase SINDRI goals and values: https://youtu.be/-d3t9ebqvhY.

STAFF HIGHLIGHTS

The SINDRI team and its influence continues to thrive thanks to movement of talent: Dr C. Nicolai has taken the reins as the new programme manager. EDF has grown with Alan Jappy and ex Bristol Sindri PhD student Ed. Horton joining to accelerate the translation of SINDRI research into industrial innovation; Dr Z. Chen has moved from Bristol starting as PDRA at the University of Manchester and will focus on weldment modelling; Prof. M. Mostafavi's international profile has unfortunately been our loss as he has been appointed to Monash University as Head of Department. Dr M. Yankova's fantastic achievements have resulted in a Research Fellow within Materials at Manchester (still linked to SINDRI). Chris Allen completed his PhD and has taken up a role with AWE.

GOVERNANCE, EQUALITY DIVERSITY AND INCLUSION (ED&I) AND RESPONSIBLE RESEARCH INNOVATION (RRI)

Responsible Research & Innovation Workshop, (February 6th, 2024, Engineers' House, Bristol) for SINDRI was led by RRI expert Vivienne Kuh from the University of Bristol. Concepts such as reflexivity and personal identity were explored in how they impact individuals' research and outputs and visualising the future impact of their research on society. Researchers also took part in an introduction to public engagement, and interrogating participants in their research. These activities provide researchers the time and space to reflect on the impact of their work and reflect on their responsibility to the public in how they develop and execute research.

Governance of SINDRI has continued through regular meetings of the steering and technical boards with the annual Steering Board meeting taking place on the 24th of January 2025 and the biannual Technical Advisory Board meeting on the 29th of October and on the 8th of April.

A number of changes have been made to the boards of the last year. Paul Spence has been replaced by Patrick Dupeyrat as he has retired from EDF Energy. Also, Fionn Dunne has reduced his work commitments such that Prof John Stairmand has now assumed the full role of chair for the technical board. Gareth Hopkin, ONR representative, has joined the technical board in 2024.

The technical boards have provided valuable input toward widening impact, while the Steering Board has focussed on potential SINDRI follow-up activities along with future potential collaborators.

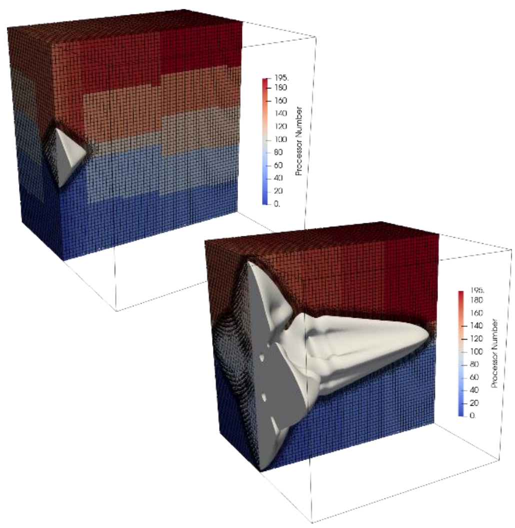
FINANCES

From the information shared with the University of Bristol, the project finances of the academic partners are on track to ensure adequate resources to take the project to completion in 2027. The University of Manchester is carrying out an optimization within the Directly Incurred fund heading with a spending review.

The transfer to EDF of new knowledge gained within SINDRI has been supported by funding from the UKRI Impact Accelerator Account Advance scheme with £60,000. The aim is to scale up the microstructure-informed modelling of residual stress development in transforming steels from laboratory specimens to engineering scale weldments.

CASE STUDIES

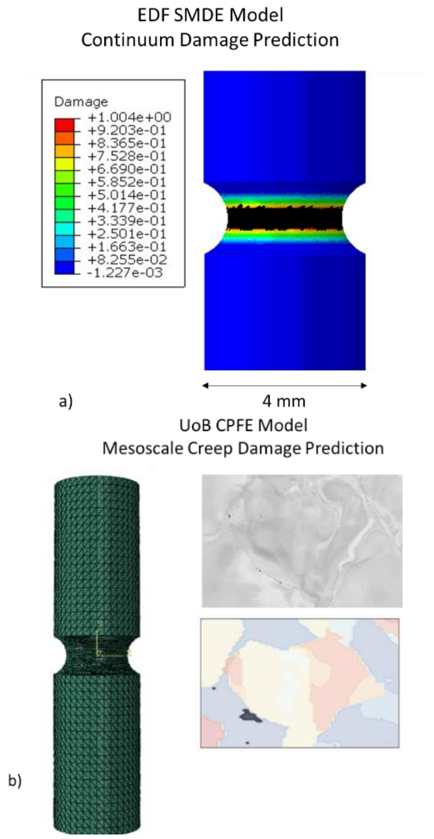
1 – Open-source high-fidelity multi-phase field solidification framework



Great strides have been made in the development of high-fidelity multi-component multi-phase field formulations that can be used to simulate phase transitions, for instance the lay-down of weldments, a common safety case challenge in the nuclear sector. In SINDRI, this framework has primarily been used to study the solidification behaviour of multi-component iron-based alloys. The developed framework will shortly be released open-source. The framework fully captures the complex interface anisotropy that leads to complex solidification morphologies.

The images show the framework in action simulating a growing dendrite in a multi-component alloy; the automatic-mesh-refinement makes it far more computationally tractable to use this high-fidelity approach on larger computational domains and number of phases.

2 - Integration of CPFE modelling into EDF's structural integrity assessment procedures



The mesoscale crystal plasticity finite element (CPFE) model for creep deformation and damage of 316H stainless steel, developed in WP1.2, has been directly compared with the Stress Modified Ductility Exhaustion (SMDE) method used by EDF Energy in the R5 structural integrity assessment procedure. This comparison is a critical step toward integrating microstructural features into the UMAT subroutines in EDF's structural assessment workflows. The images show the damage prediction of EDF SMDE model (a) and UoB CPFE model (b).

In the short term, these developments will impact the life extension strategy for Sizewell B nuclear power plant, where R5-based assessments are critical for decision-making on component integrity. In the longer term, the incorporation of CPFE into EDF's structural integrity workflows has the potential to transform industry-standard assessment procedures for high-temperature power plant components.