Damage Accumulations Predictions For Boiler Components Via Microstructurally Informed Material Models

FY22 FECM Spring R&D Project Review Meeting
Crosscutting Research. High Performance Materials Program
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Outline

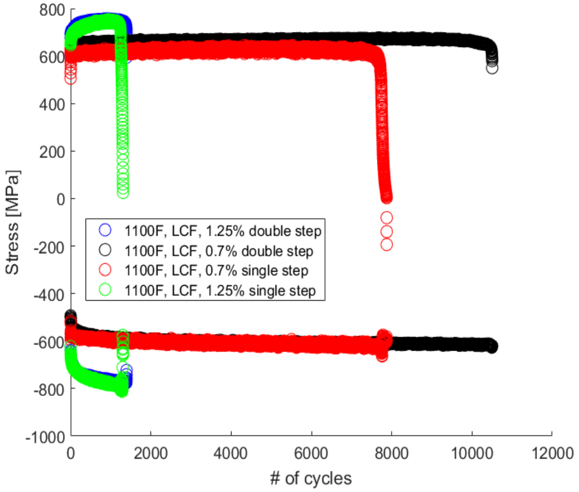
- Technical background of the project
- Statement of project objectives
- Technical approach to achieving the project goals
- Conclusions and next steps

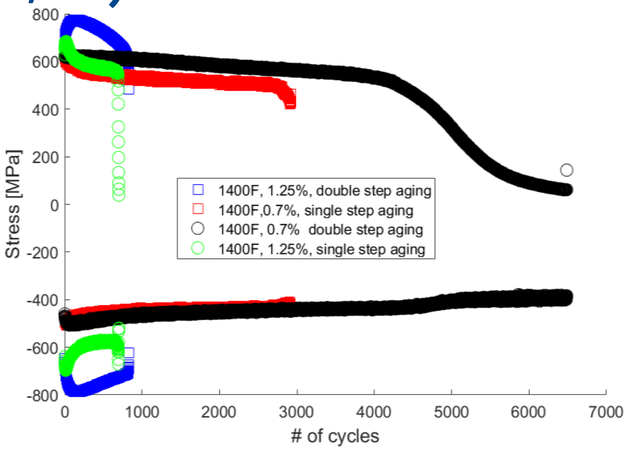
The authors wish to thank Thomas Sambor and Steven Kung (Electric Power Research Institute) for technical discussions and information about Grade 91 superheater outlet header, Michael Schuster, David Bodner (GE Research) for mechanical testing and DIC measurements and Mallikarjun Karadge (GE Research) for microstructure characterization.

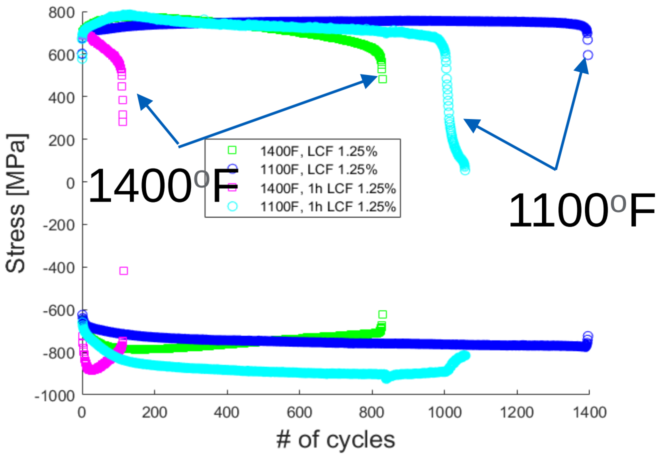
Technical Background

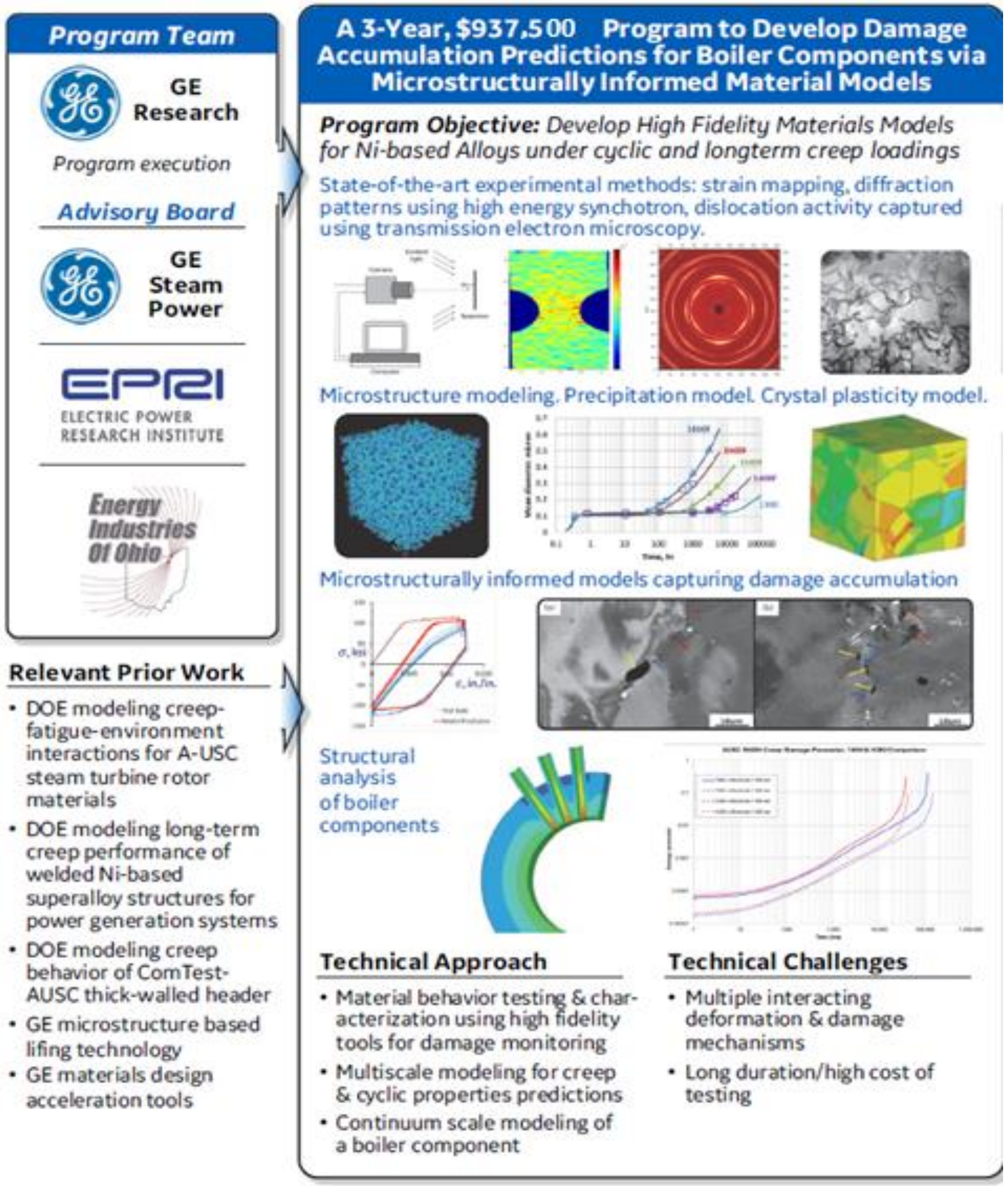
Develop physically informed models to capture degradation and predict durability of Nickel-based superalloys during cyclic operations in USC and A-USC power plants components where thermo-mechanical fatigue and creep damage are occurring at the same time. 300,000h operation.

1100 °F to 1400 °F/ Haynes 282









Statement of project objectives

- **Provide physically informed models, capturing the microstructural changes taking place in the industrial components under cyclic loading and exposure to high stress and temperature for long operating life**

Task 2. 2020-2021

Develop Quantitative Understanding of Microstructure Evolution, Deformation and Damage Mechanisms of H282

2.1. Perform High Temperature Tensile and Isothermal Low Cycle Creep-Fatigue Tests (Completed)

2.2 Perform cyclic testing on single step aging heat-treated Haynes 282 alloy (on track)

2.3. Perform Thermo-Mechanical Fatigue Tests (Completed)

2.4. Characterize Microstructures of Test Specimens from Sub-Tasks 2.1, 2.2 and 2.3 (Completed)

Task 3. 2020

Perform Microscale Modeling of Microstructure and Strain Evolution

3.1. Perform Modeling of the Rate of Precipitation and Growth of Gamma Prime Particles in the Haynes 282 Microstructure (Completed)

3.2. Perform Crystal Plasticity (CP) Modeling of Haynes 282 (Completed)

Task 4. 2020-2022

Develop Continuum Damage Mechanics (CDM) Model of Haynes 282

4.1. Develop CDM Model Framework (Completed)

4.2. Calibrate, Validate and Document the CDM Model Framework(Completed)

4.3. Integrate CDM Model Framework into Finite Element Analysis Software (Completed)

4.4. Couple Transient Thermal Analysis to CDM Model Framework in Finite Element Analysis Software (on track)

Task 5. 2021-2022

Perform Structural Modeling of a Thick Wall Boiler Component

5.1 Perform Baseline CDM Analyses of a Thick Wall Boiler Component (on track)

5.2. Perform Damage Sensitivity Studies on a Thick Wall Boiler Component (on track)

Plasticity and Creep Material Model

$$\varepsilon^{total} = \varepsilon^{elastic} + \varepsilon^{total\_inelastic} + \varepsilon^{thermal}$$ total strain

$$\varepsilon^{total\_inelastic} = \varepsilon^{plastic} + \varepsilon^{creep}$$ total inelastic strain

$$E\varepsilon^{elastic} = \sigma^{eff}$$ elastic strain

$$\omega^{total} = \omega^{plastic} + \omega^{creep}$$ total damage variable

$$\sigma^{eff} = \frac{\sigma}{1-\omega^{total}}$$ effective stress

$$\rho = \rho_o + (\rho_f - \rho_o)(1 - \exp(-\varepsilon^{total\_inelastic}))$$

Micro structural parameters/ Material properties: E, b, f, λ...

Fitted parameters $C, \gamma, D_{pl}, D_{cr}$

Internal variables account for

- **Dislocation density evolution** ρ
- **γ' evolution with time/ temperature** r
- **Cavities growth** $\omega^{total}, \omega^{plastic}, \omega^{creep}$ ρ
- **Dislocations- precipitates interactions** σ_p
- **Dislocations- dislocations interactions** σ_o

$\varepsilon^{plastic}$ determined from the consistency conditions
df= 0 where $f = |\sigma^{eff} - \sigma_p| - \sigma_o$

$$\sigma_o = M \cdot G \cdot b\sqrt{\rho}$$ Isotropic hardening

$$d\sigma_p = C d\varepsilon^{plastic} - \gamma \sigma_p |d\varepsilon^{plastic}|$$ Kinematic hardening

$$\omega^{plastic} = D_{pl} \int_0^t \dot{\varepsilon}^{plastic}\, ds$$

Plasticity

$$\varepsilon^{creep} = \varepsilon^{disloc} + \varepsilon^{diff}$$

$$\dot{\varepsilon}^{disloc} = A(\rho, f) sinh \left\langle \lambda b^2 \frac{|\sigma^{eff} - \sigma_c| - \alpha\sigma_o}{MkT} \right\rangle$$

$\dot{\varepsilon}^{diff}$=f(σ^{eq}, D_{cr})

Soare, Shen, Cedro III, Superalloys 2020

$$\omega^{creep} = D_{cr} \int_0^t \dot{\varepsilon}^{creep}\, ds$$

Creep

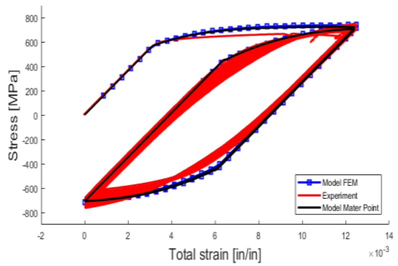
Model Predictions and Experiments

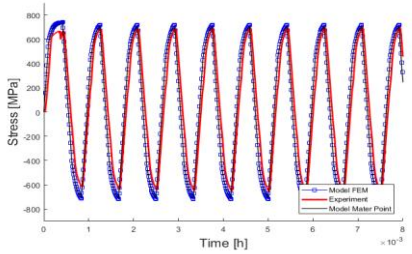
Model – FEM

Model – Material Point

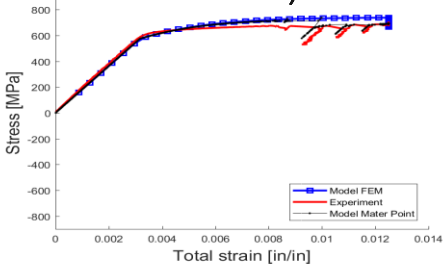
Experiment

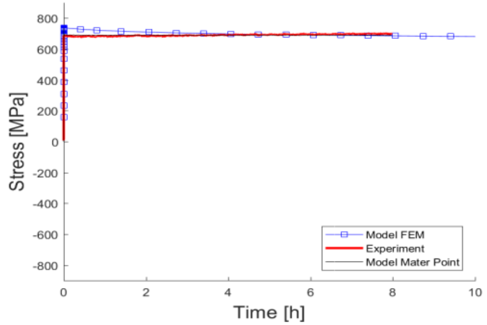
LCF. 1100ºF. 20cmp



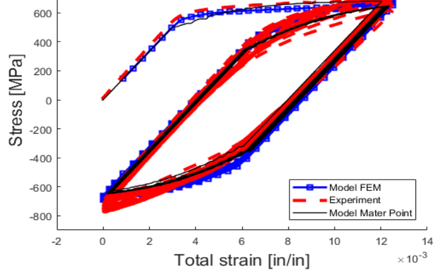


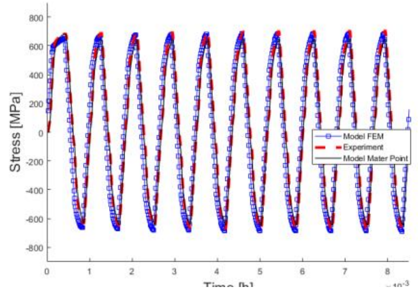
Relaxation, 1100ºF



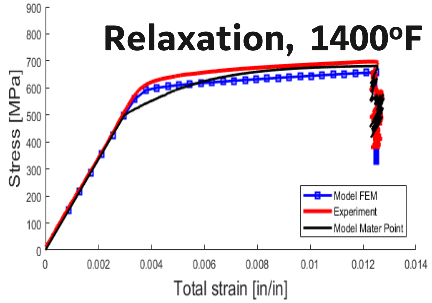


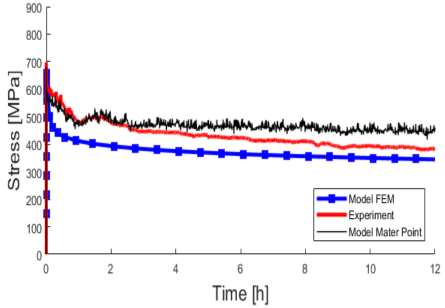
LCF, 1400ºF, 20cmp



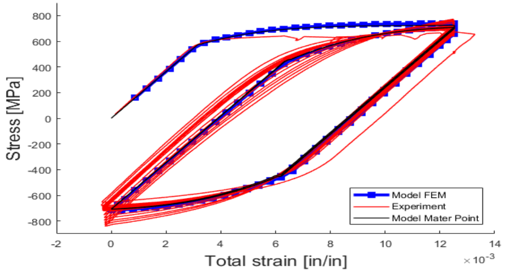


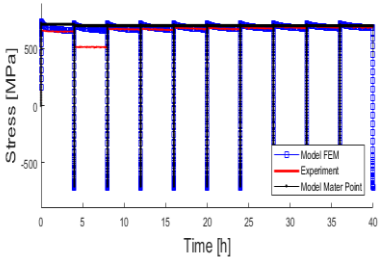
Relaxation, 1400ºF



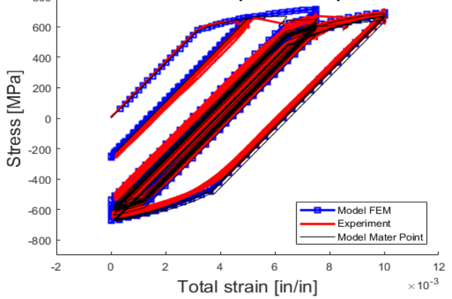


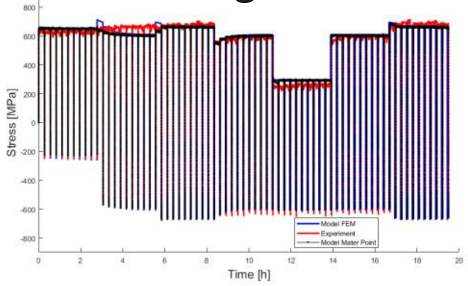
SPLCF, 1100ºF, 4h hold time



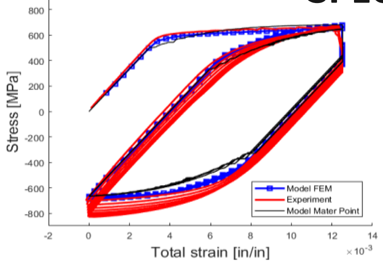


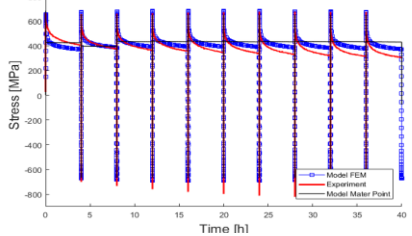
1100ºF, 0.5%, 0.7% and 1% alternating strain



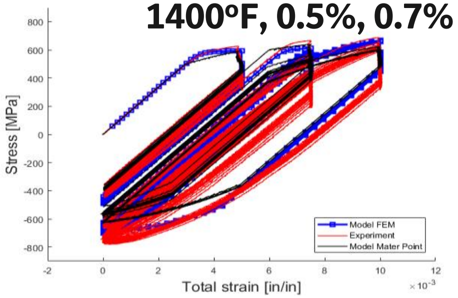


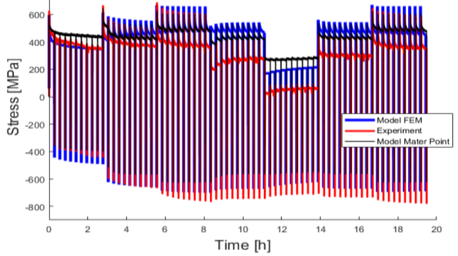
SPLCF, 1400ºF, 4h hold time





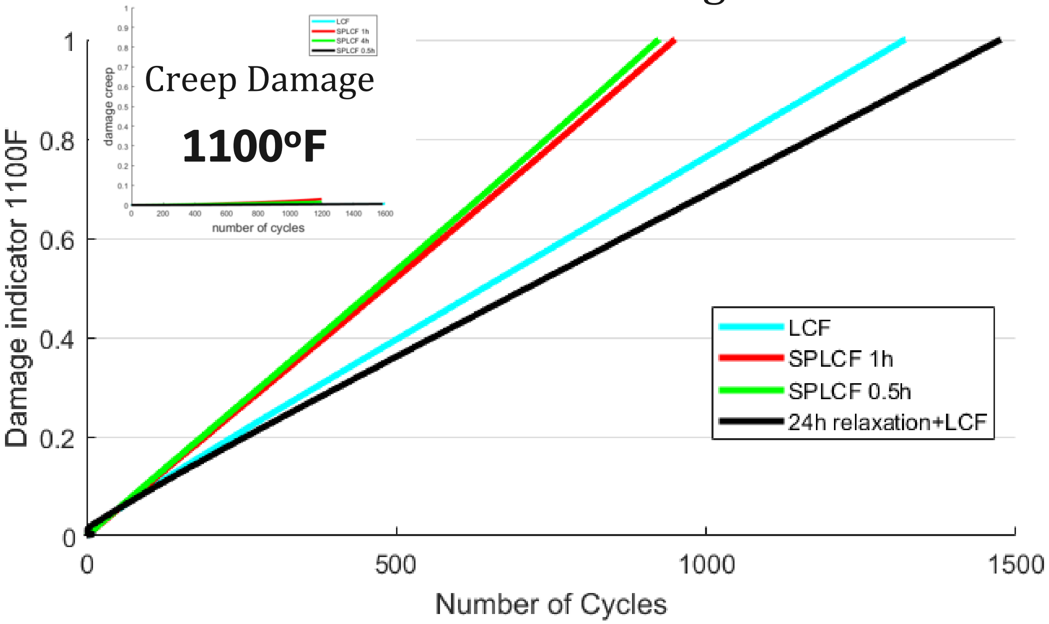
1400ºF, 0.5%, 0.7% and 1% alternating strain



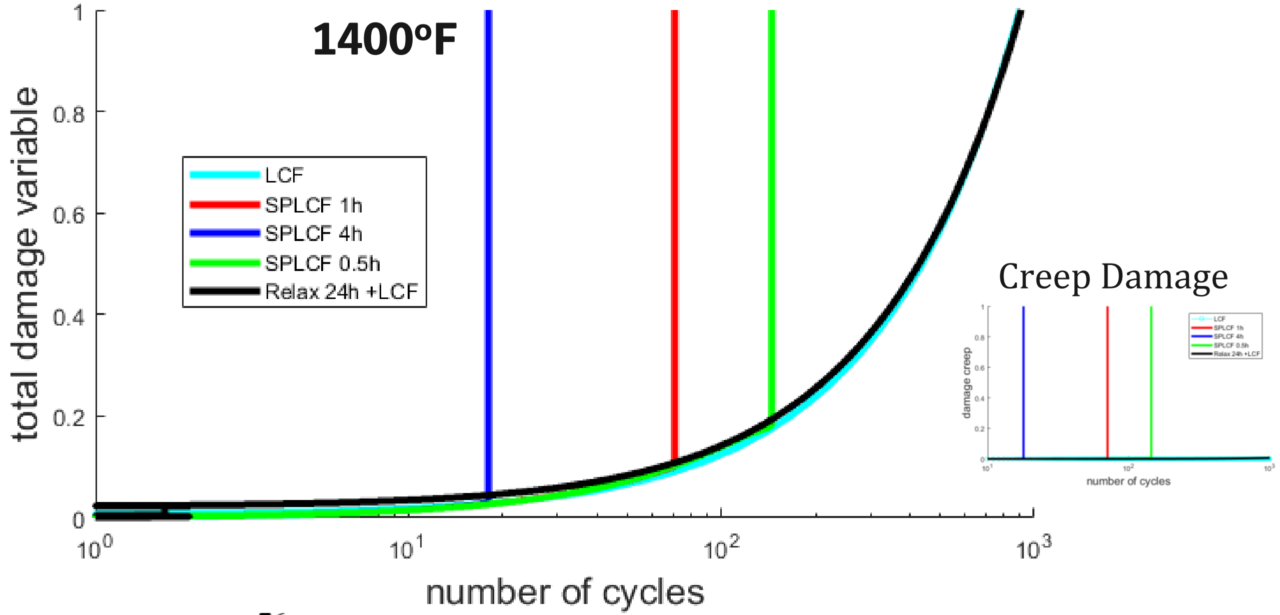


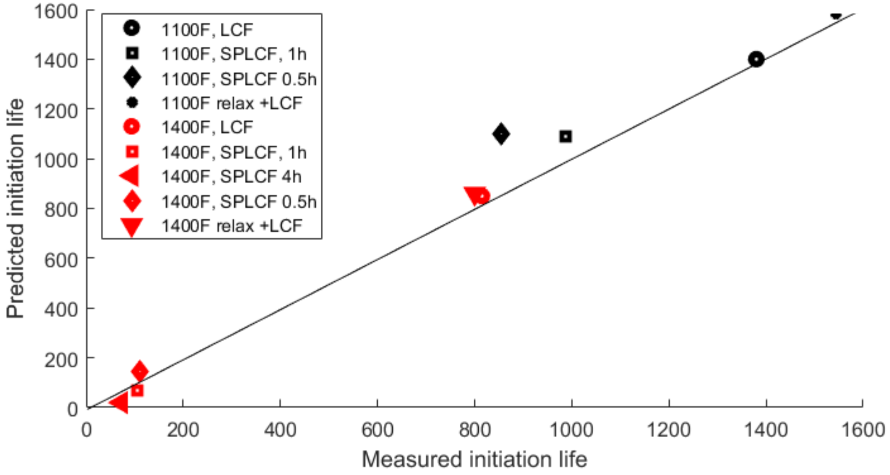
Model Predictions and Experiments

Total Damage $\omega^{plastic} + \omega^{creep}$



Total Damage $\omega^{plastic} + \omega^{creep}$

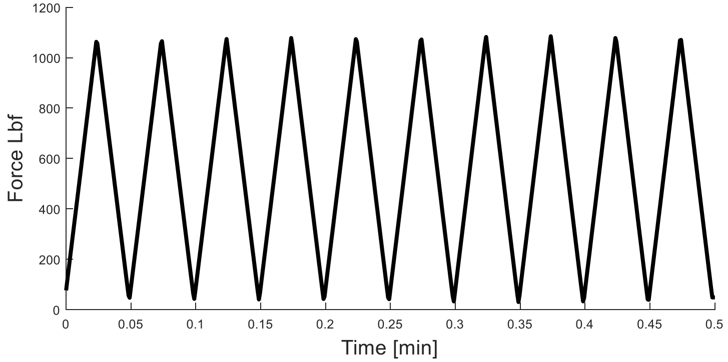




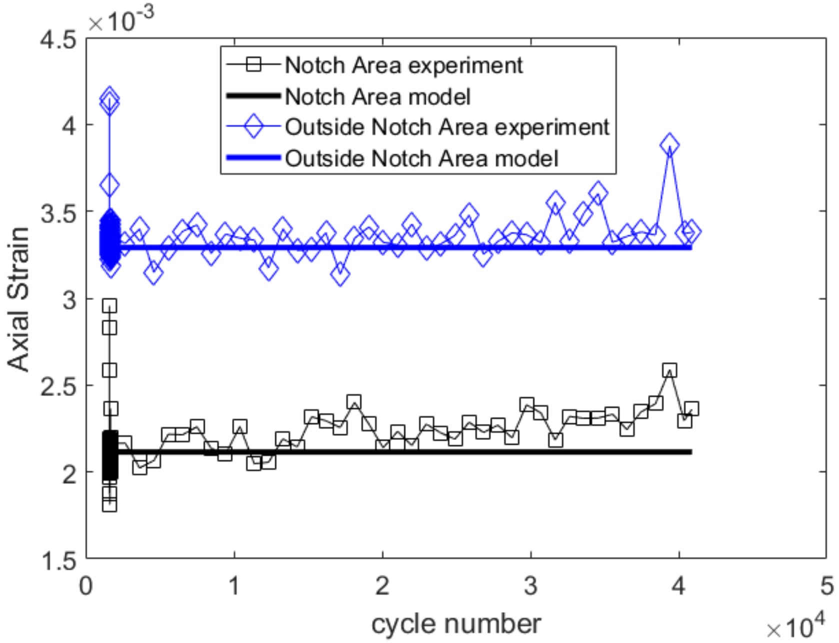
Model Predictions and Experiment DIC Measurements on Notch Tests

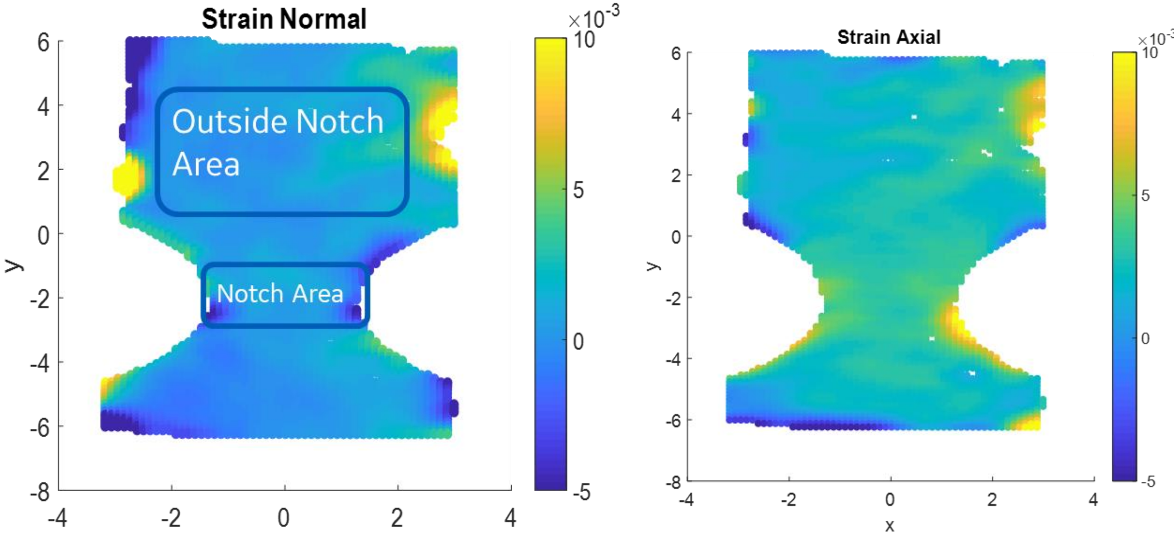
Stress controlled cyclic loading at 1100ºF

Applied Force

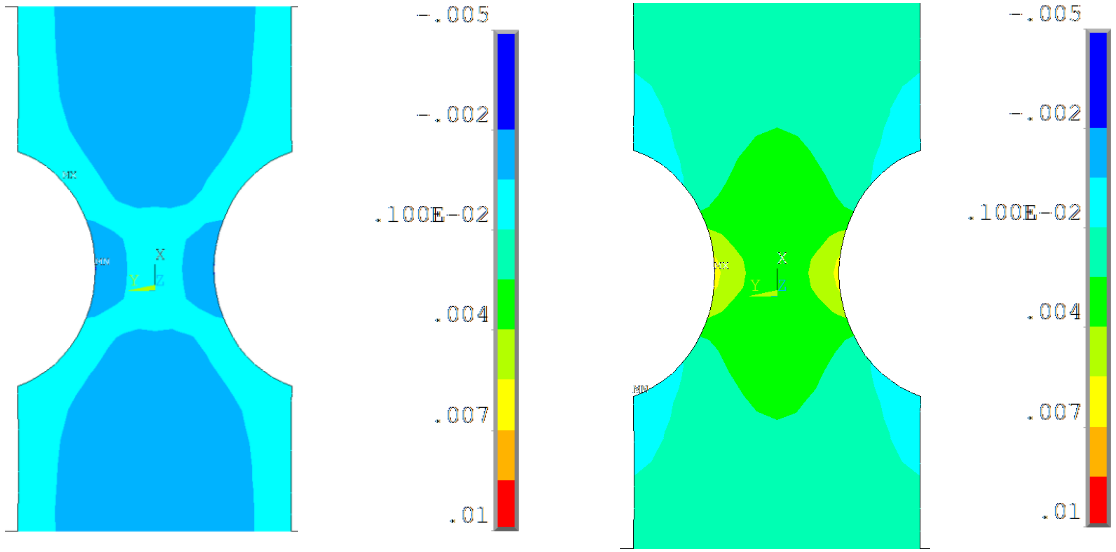


Measured And Predicted Strain





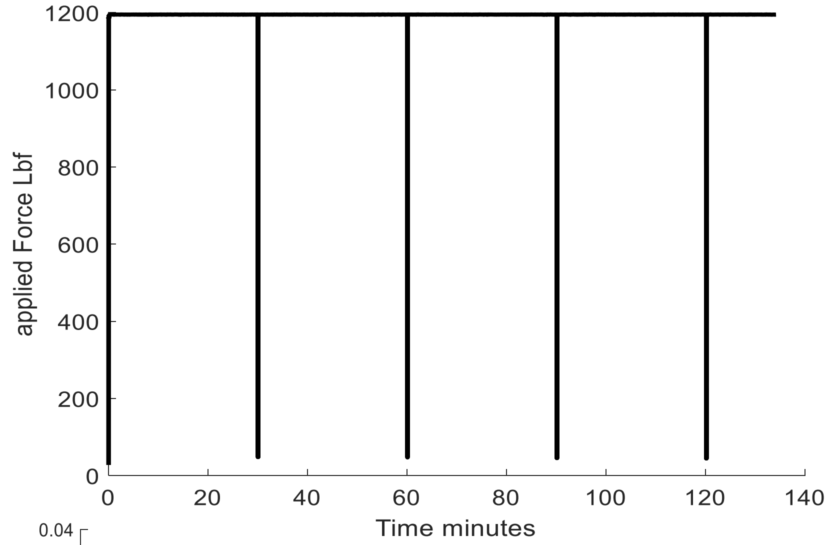
DIC Measured

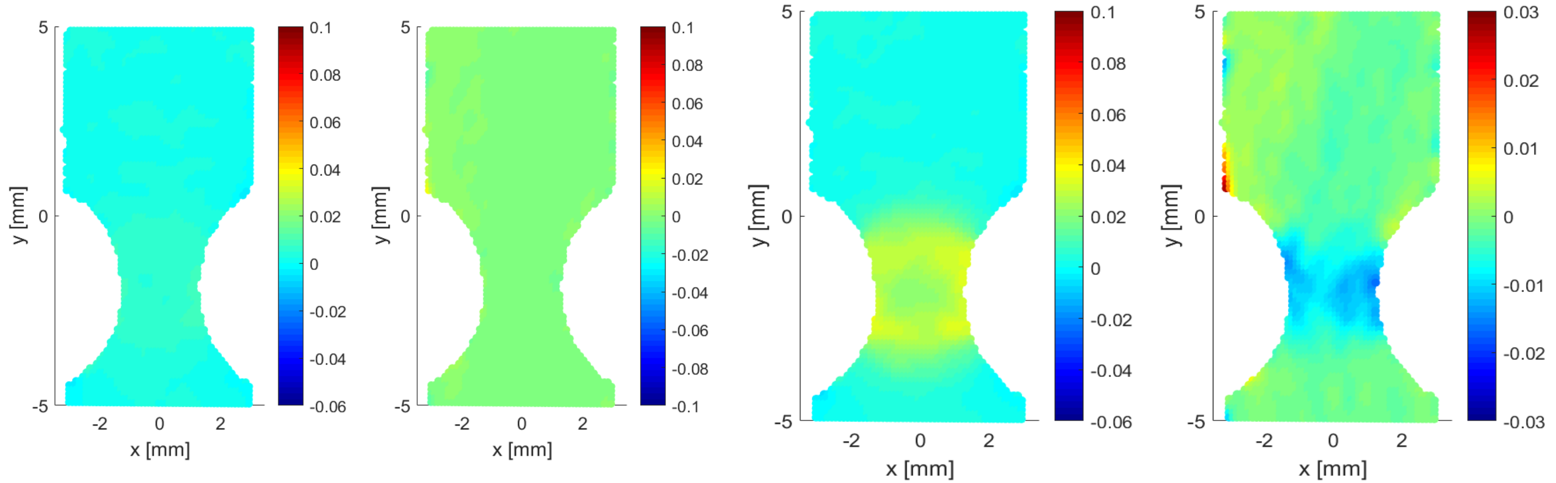


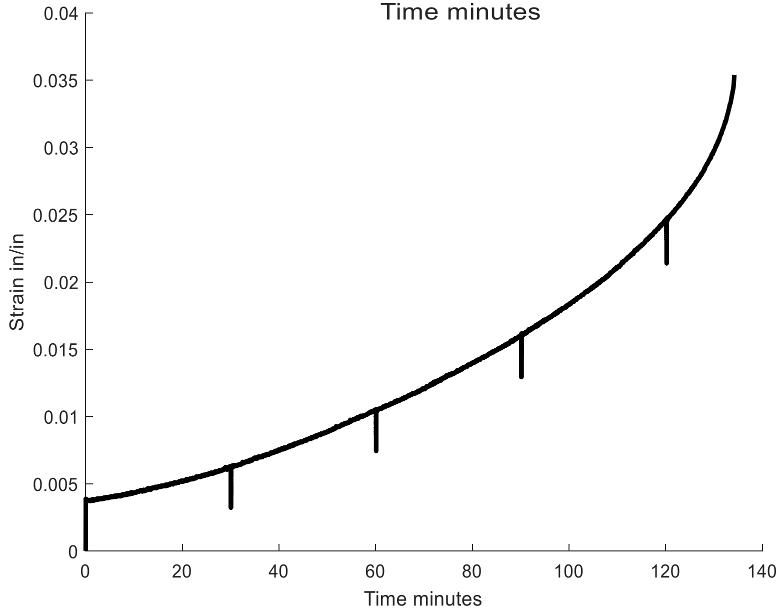
Predicted

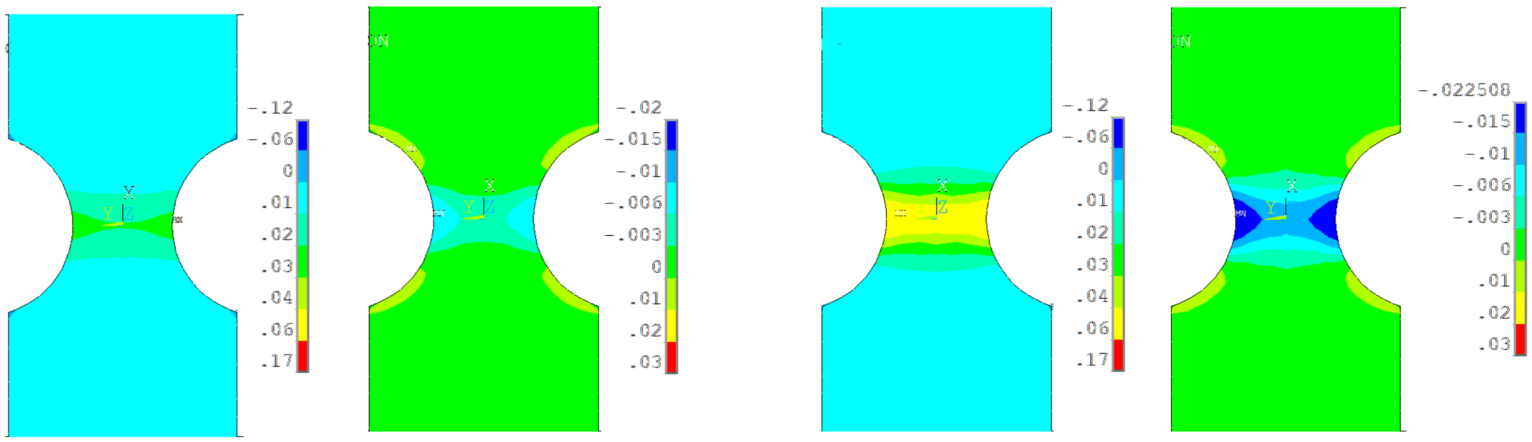
Model Predictions and Experiment DIC Measurements on Notch Tests

Stress controlled cyclic loading at 1400ºF

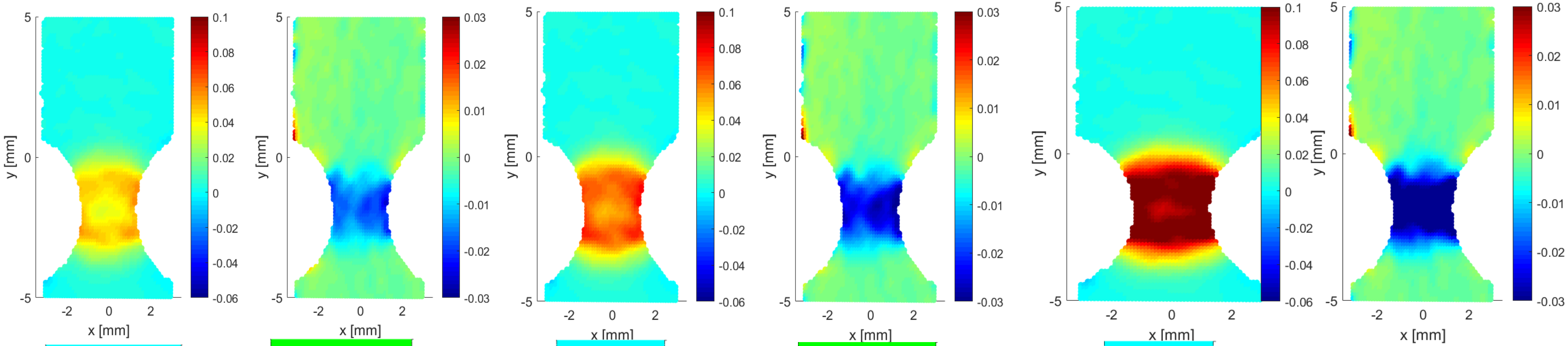




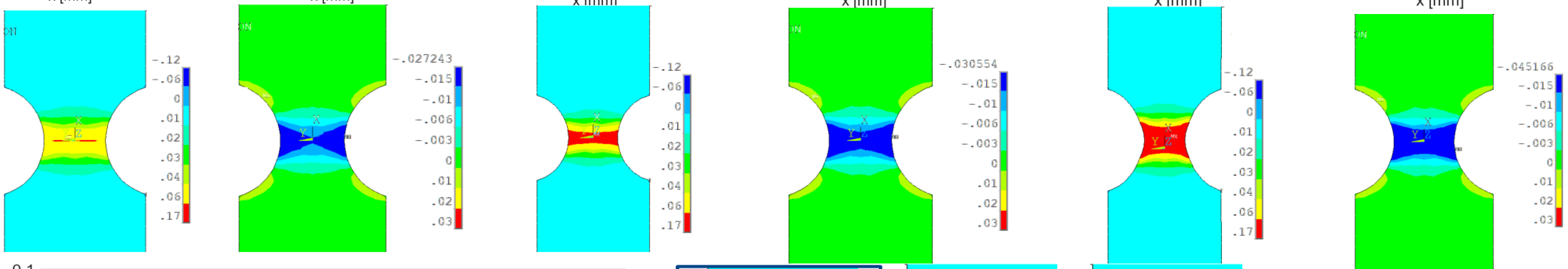




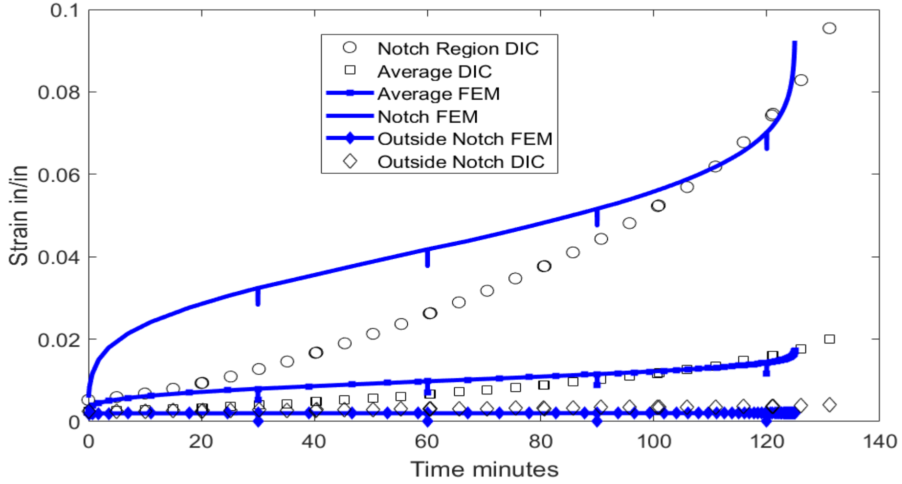
Model Predictions and Experiment DIC Measurements on Notch Tests

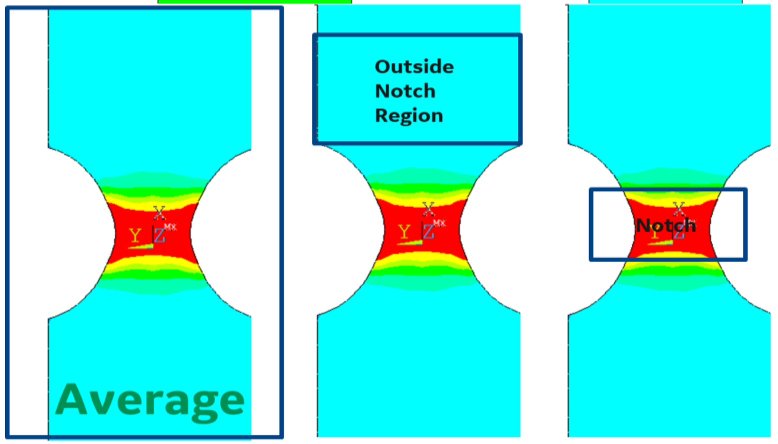


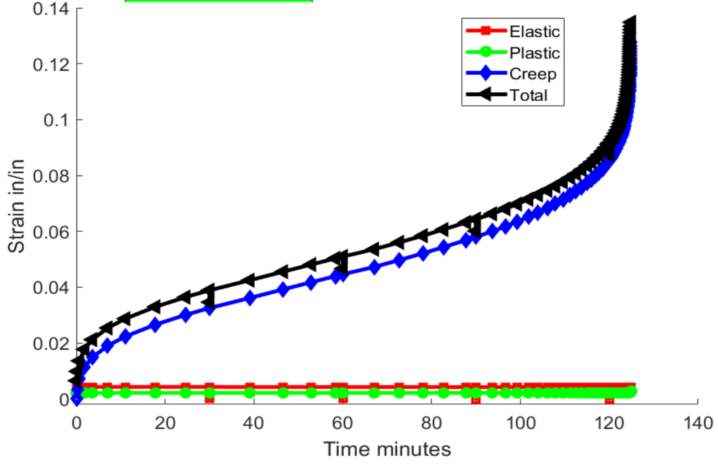
DIC
Strain
Measurements



Model
Predictions

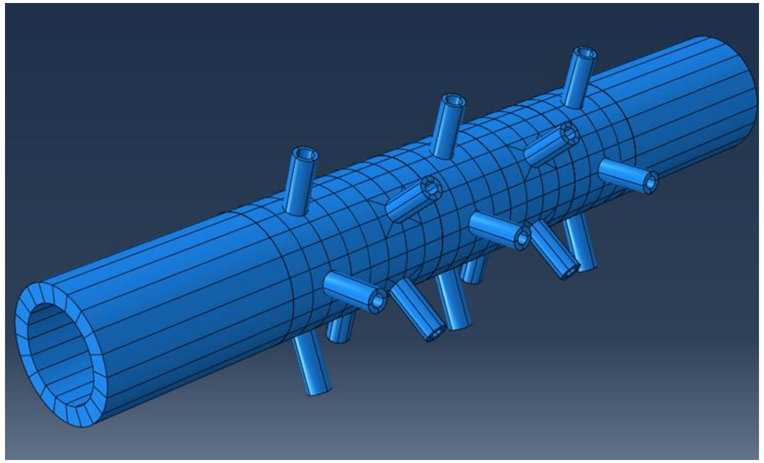


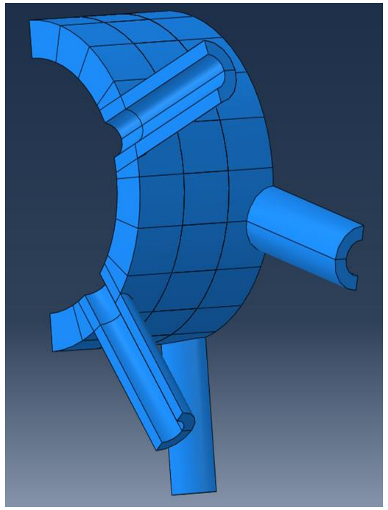




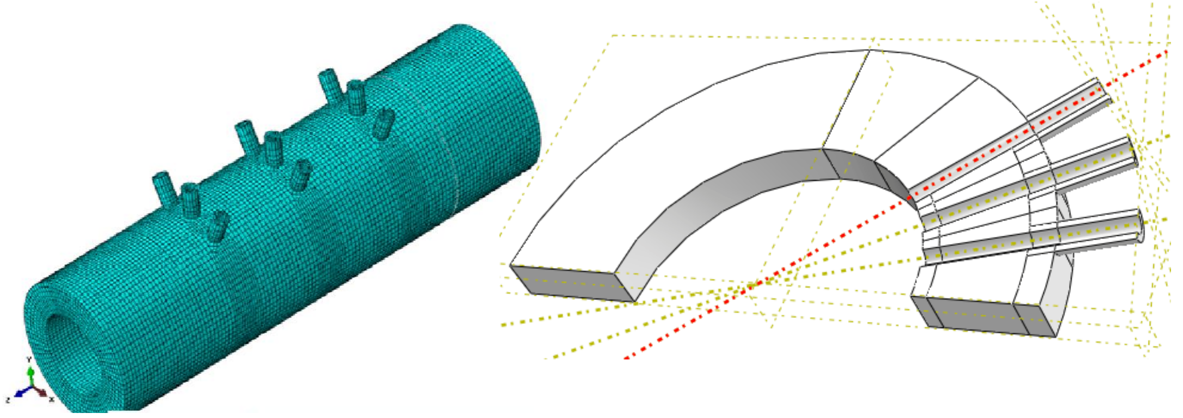
❑ Perform Baseline CDM Analyses of a Thick Wall Boiler Component (in progress)

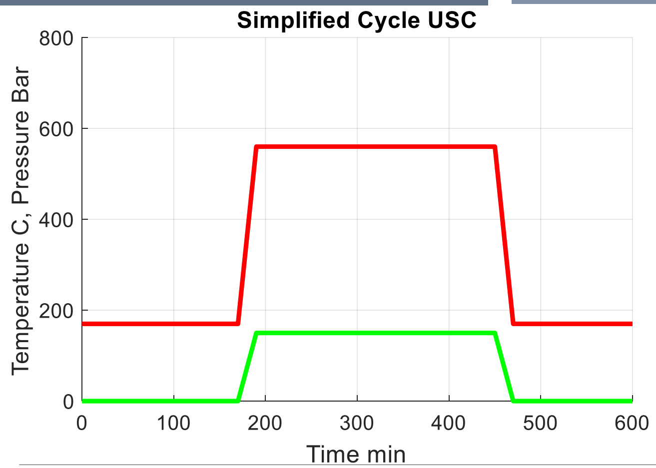
1100F (USC conditions) - benchmark configuration
Grade 91 outlet header

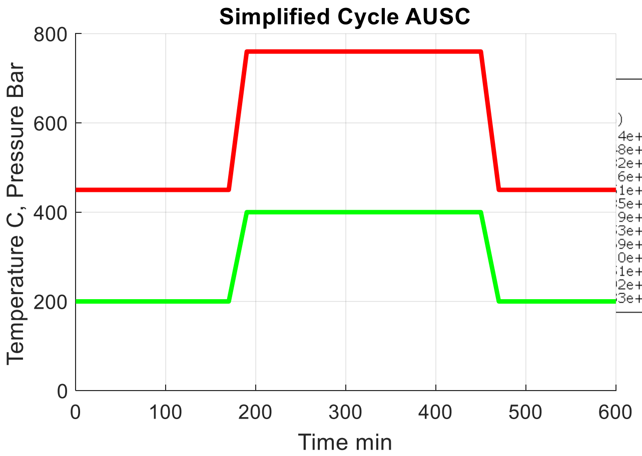


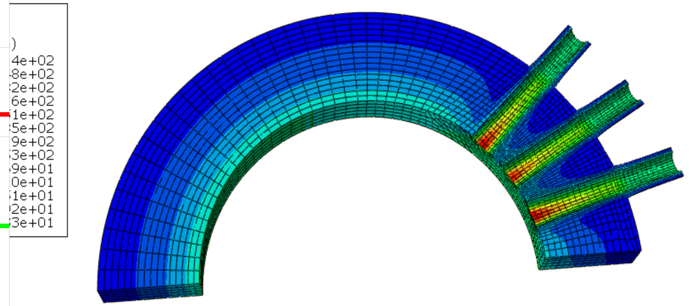


1400F (AUSC conditions) –H282 alloy header (newly developed model)









Concluding Remarks

06/2021-04/2022

- Developed framework for continuum damage model coupling creep and cyclic plasticity. Model verified against uniaxial tests.
- Completed LCF, SPLCF tests on notched specimens with local strain measurements
- Completed model validation on multiaxial stress tests (using local strain measurements)
- Select USC and AUSC header geometries and loading conditions

Next Steps

Demonstrate material model applicability at component level

- Perform analysis of a thick wall boiler header – baseline configuration
- Perform damage sensitivity studies on a thick wall boiler header