# Damage Accumulations Predictions For Boiler Components Via Microstructurally Informed Material Models

**Crosscutting Research and Advanced Energy Systems Project Review Meeting**
**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

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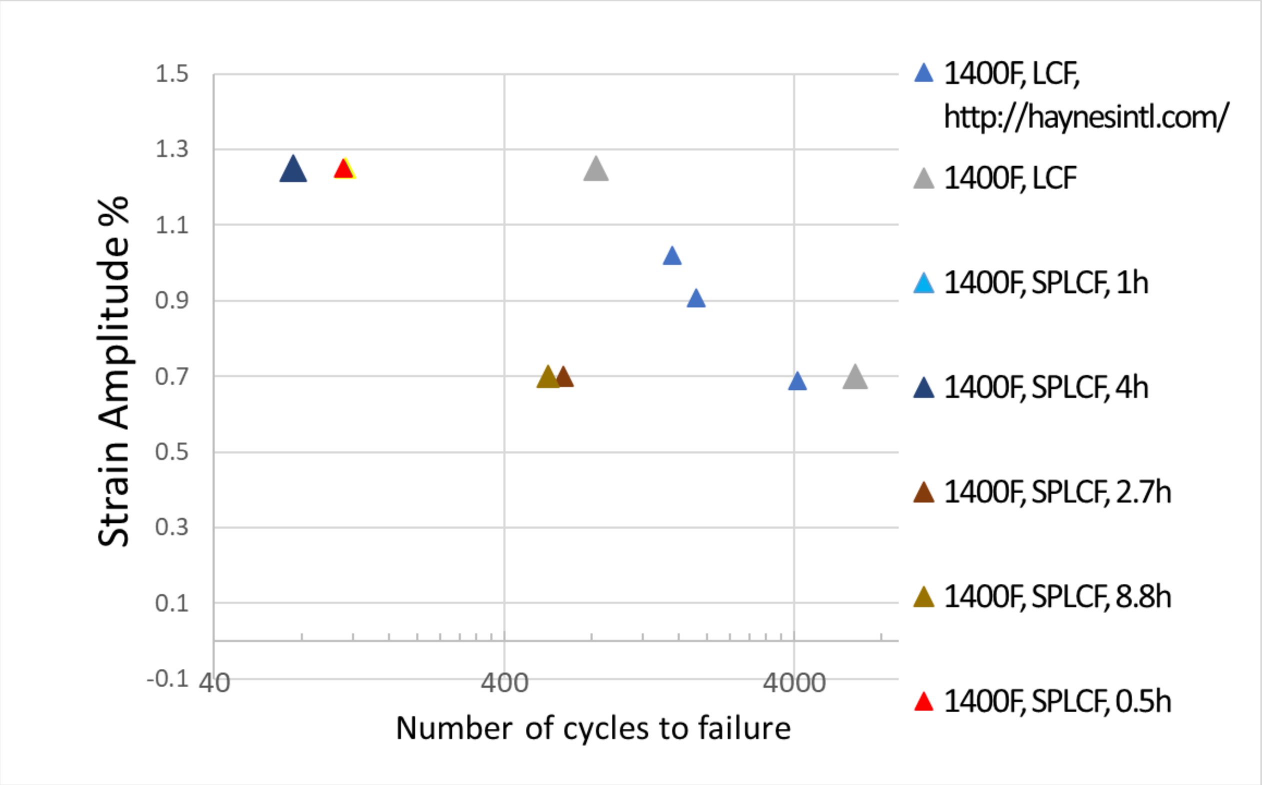
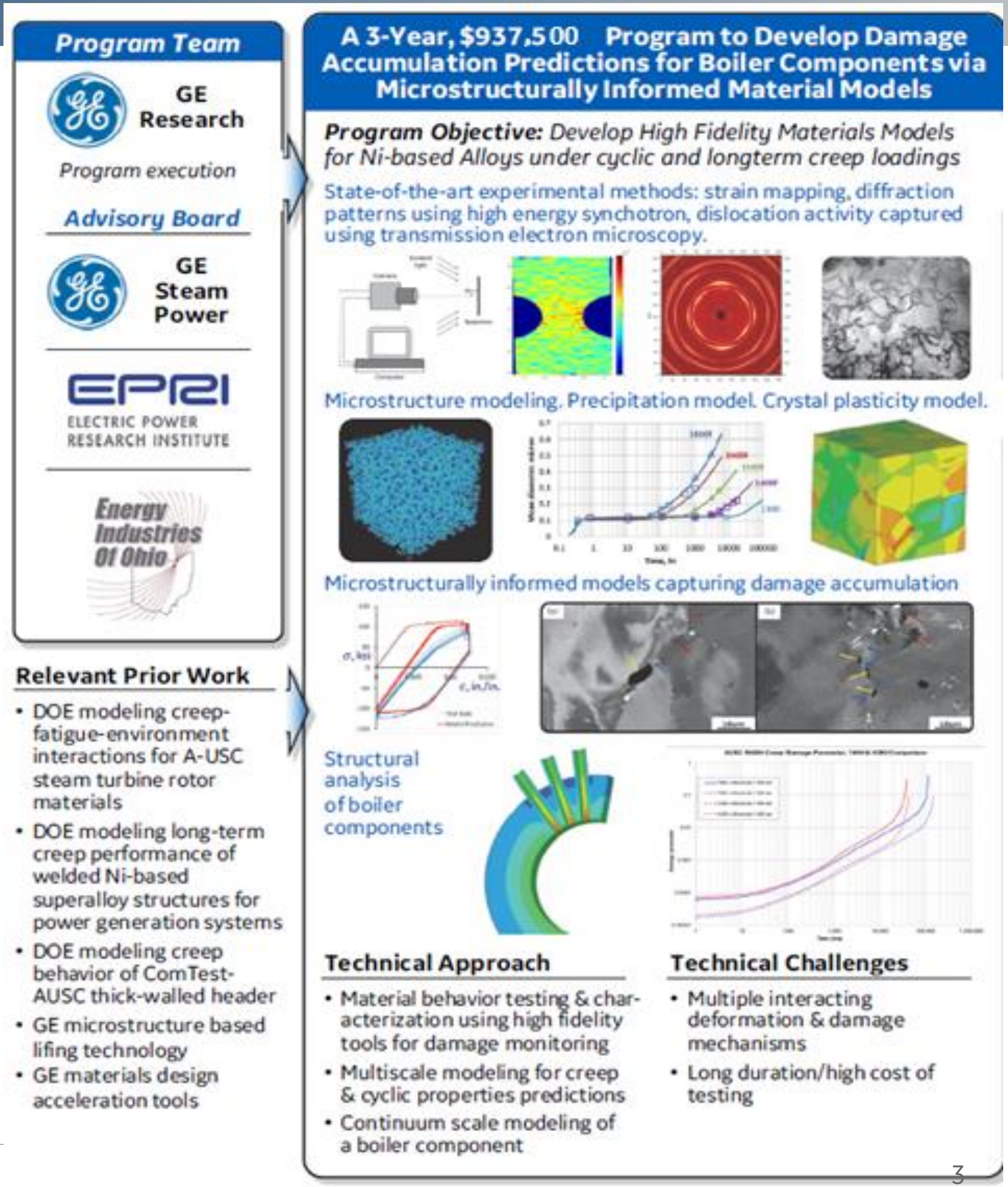
# Technical Background

Develop physically informed models to capture degradation and predict durability of Nickel-based superalloys during cyclic operations in fossil energy (FE) 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/ Boiler headers



# 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)
*Milestone: 09/30/2021*

## 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)
*Milestone: 09/30/2021*

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

## Task 4. 2020-2021

**Develop Continuum Damage Mechanics (CDM) Model of Haynes 282**

4.1. Develop CDM Model Framework (Completed)
*Milestone: 09/30/2021*

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

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

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)

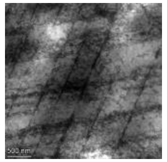
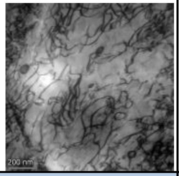
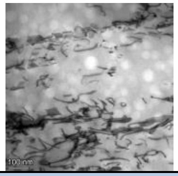
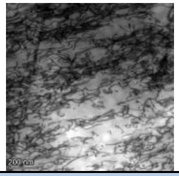
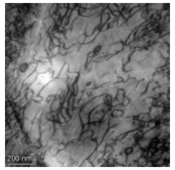
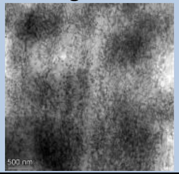
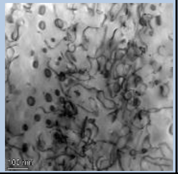
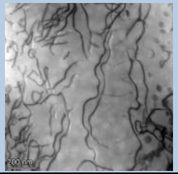
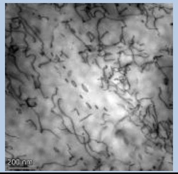
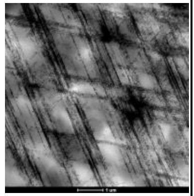
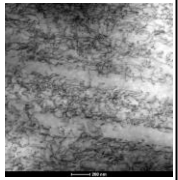
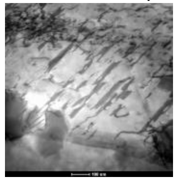
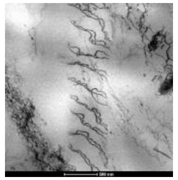
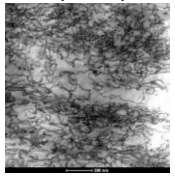
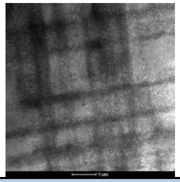
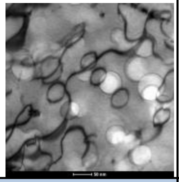
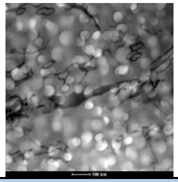
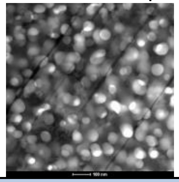
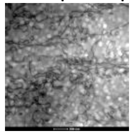
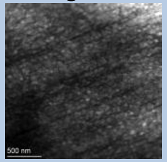
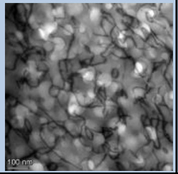
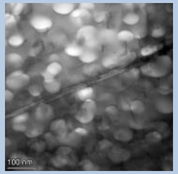
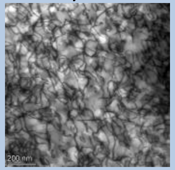
5.2. Perform Damage Sensitivity Studies on a Thick Wall Boiler Component (on track)

# Mechanical Tests (Task 2)

| | Specimen number | Type of test | Temperature | Max strain | Cycles to initiation | cycles to failure | status |
|---|---|---|---|---|---|---|---|
| ⇨ | L2 | LCF | 1400F | 1.25% | 815.00 | 828 | failed |
| ⇨ | L3 | LCF | 1100F | 1.25% | 1380.00 | 1,395 | failed |
| | L4 | LCF | 1100F | 0.70% | 10400.00 | 10,503 | failed |
| ⇨ | L5 | SPLCF, 1hour | 1400F | 1.25% | 105.00 | 114 | failed |
| ⇨ | L6 | SPLCF, 1 hour | 1100F | 1.25% | 987.00 | 1056 | failed |
| ⇨ | L7 | SPLCF, 4 hours | 1400F | 1.25% | | interrupted | interrupted |
| ⇨ | L8 | SPLCF, 4 hours | 1100F | 1.25% | | interrupted | interrupted |
| ⇨ | L10 | SPLCF, 4 hours | 1400F | 1.25% | 72.00 | 75 | failed |
| | L11 | relaxation | 1400F | 1.25% | | discontinued | discontinued |
| | L12 | relaxation | 1100F | 1.25% | | discontinued | discontinued |
| ⇨ | L13 | SPLCF, 0.5 hours | 1100F | 1.25% | 855.00 | 862 | failed |
| | L14 | Complex loading | 1100F | multiple | | | completed, not failed |
| ⇨ | L15 | SPLCF 0.5h | 1400F | 1.25% | 110 | 111 | failed |
| ⇨ | L16 | Combined: first hold 24h then pure LCF | 1400F | 1.25% | | 802 | failed |
| ⇨ | L17 | Combined: first hold 24h +then pure LCF | 1100F | 1.25% | 1545.00 | 1609 | failed |
| ⇨ | L18 | SPLCF 4h hold | 1400F | 1.25% | interrupt 35 cycles (half life) | | discontinued after 35 cycles (half life) |

⇨ Microscopy analysis performed

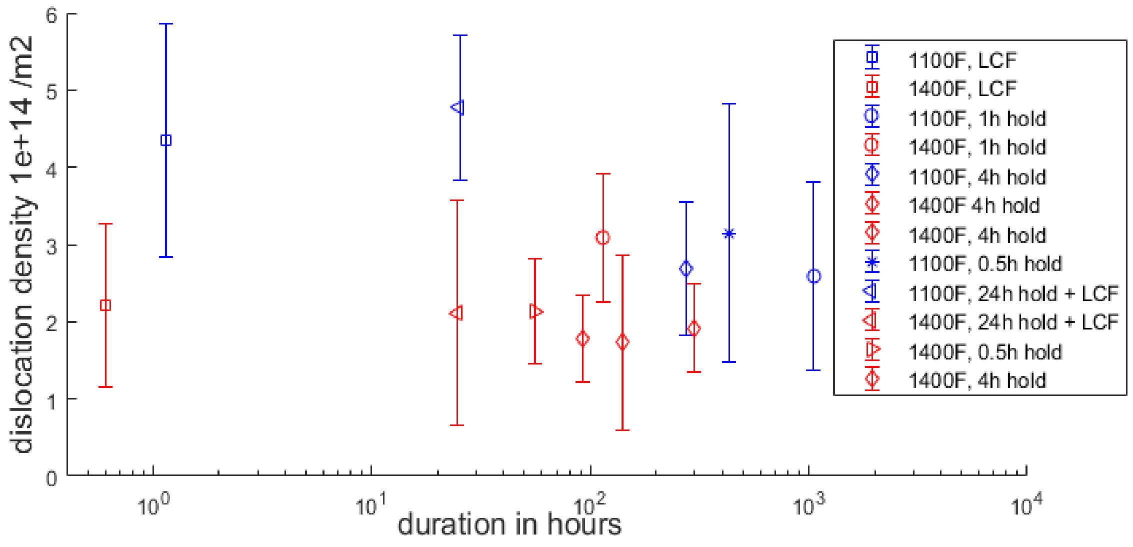
# Mechanical Tests. Deformation Mechanisms During LCF, SPLCF Loading

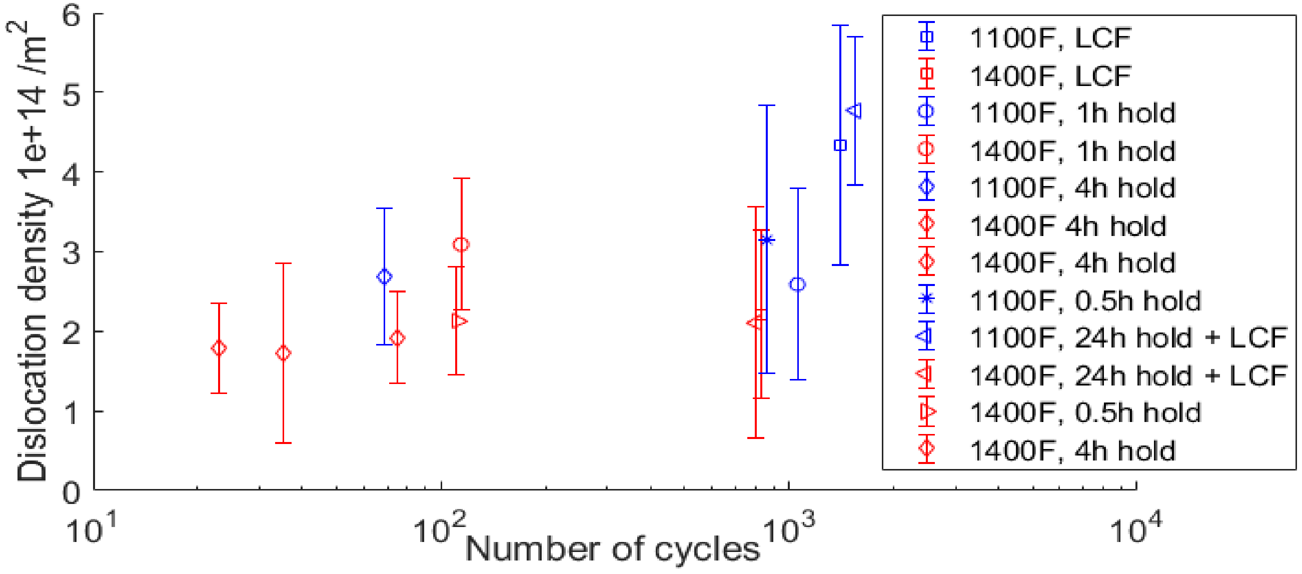
| **Label** | Localization | ½<110> activity | Orowan bypass / loops/climb | ½<110> Dissociation | Pair activity APB shear | Dislocation Density |
|---|---|---|---|---|---|---|
| **1100F LCF 1395 (L3)** | Localized<br> | Dominant | Yes<br> | Yes<br> | occasional<br> | medium<br> |
| **1400F LCF 828 (L2)** | Homogeneous<br> | Dominant | Yes<br> | no dissociation observed | occasional<br> | low<br> |
| **1100F SPLCF 0.5h 862 (L13)** | Localized<br> | Dominant | Yes<br> | occasional in γ<br> | occasional<br> | medium<br>multiple slip bands<br> |
| **1100F SPLCF 1h 1056 (L6)** | Localized<br> | Dominant | Yes<br> | occasional<br> | occasional in γ<br> | High,<br>multiple slip bands<br> |
| **1400F SPLCF 1h 114 (L5)** | both heavy localization + homogeneous<br> | Dominant | Yes + more cross slip +climb<br> | Some micro-twinning<br> | Not observed | high dislocation density + debris<br> |

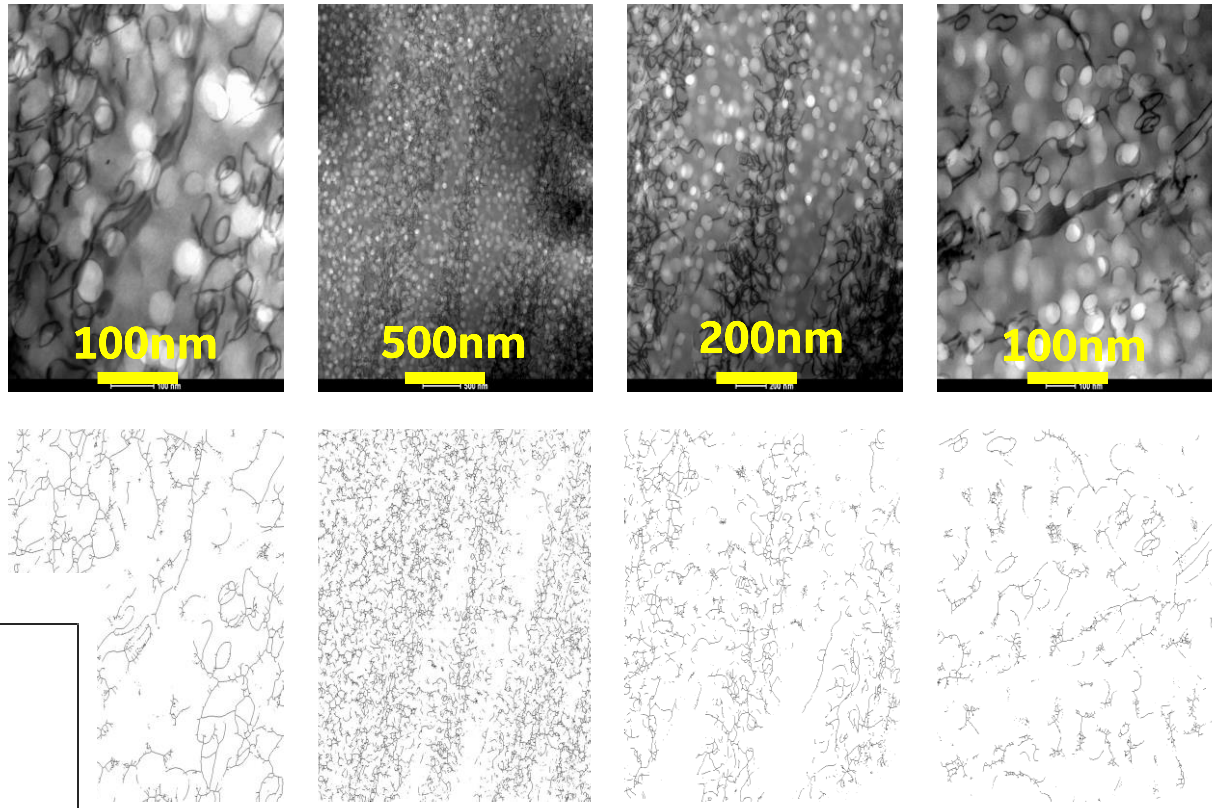
- the dominant dislocation activity was slip in the {111} planes and ½ [110] directions
- cross-slip was observed in almost all samples tested at 1400°F
- more localized deformation at 1100°F, with multiple narrow slip bands
- homogenous at 1400°F

- Orowan dislocation loops around $\gamma'$ precipitates in all specimens investigated
- dislocation pairs activities (and APB shear) were occasionally observed at 1100°F
- 1400°F, especially with hold time, additional climb mechanisms were observed

# Dislocation Density Measurements




1100°F – small increase of dislocation density with the number of cycles

1400°F - very small variation with the number of cycles

# 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

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

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

Dislocation density

**Micro structural parameters/ Material properties: E, b, f, $\lambda$...**

**Fitted parameters**

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

**Internal variables**

$\omega^{total}, \omega^{plastic}, \omega^{creep}\ \rho, \sigma_o, \boldsymbol{\sigma_p}$

$\varepsilon^{plastic}$ 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

$\omega^{plastic} = D_{pl}\varepsilon^{plastic\_accumulated}$

**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($\sigma^{eq}$, $D_{cr}$)

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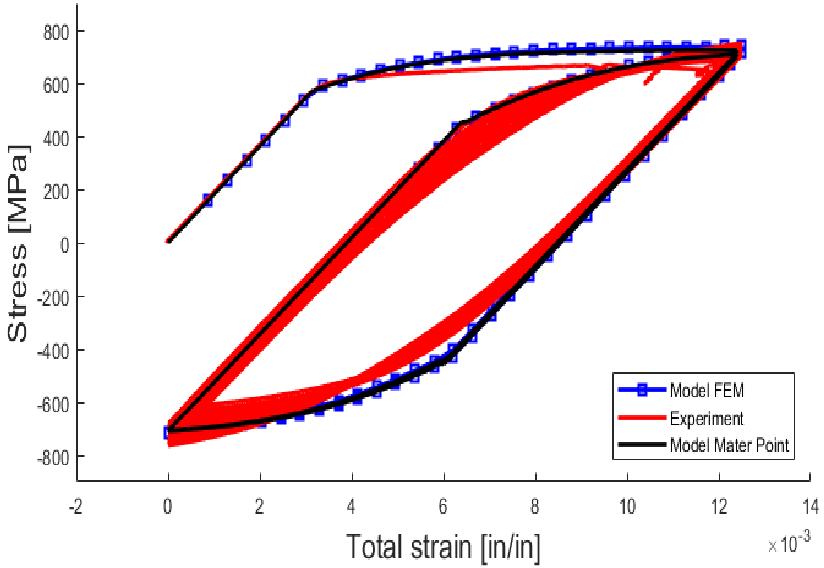
$\omega^{creep} = D_{cr}\int_0^t \dot{\varepsilon}^{creep}\, ds$

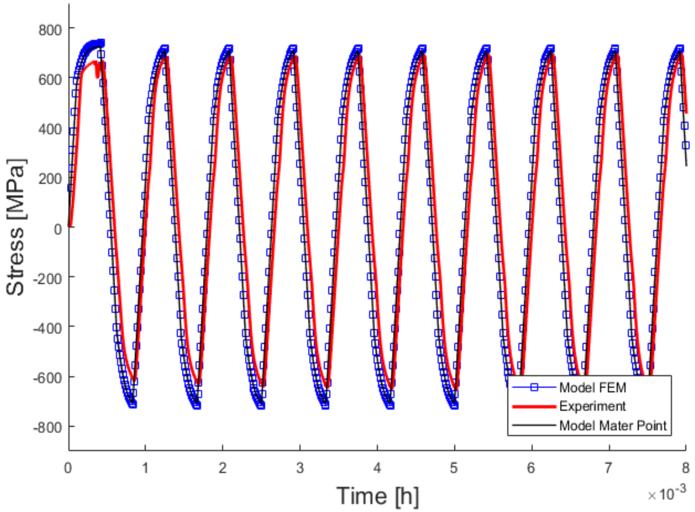
**Creep**

# Model Predictions and Experiments

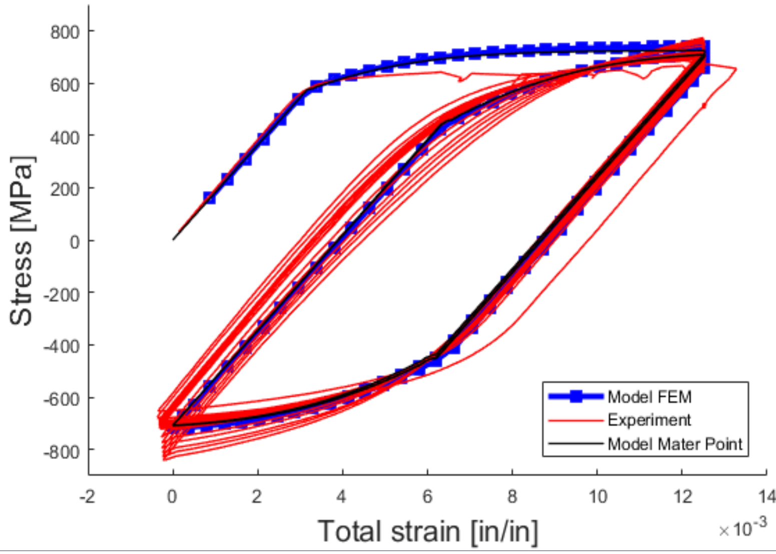
LCF, 1100°F
1.2% imposed strain
20cmp

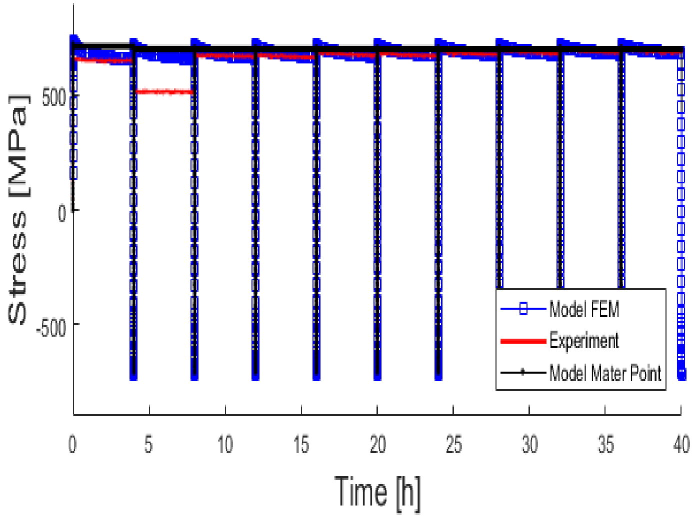
Model – FEM
Model – Material Point
Experiment



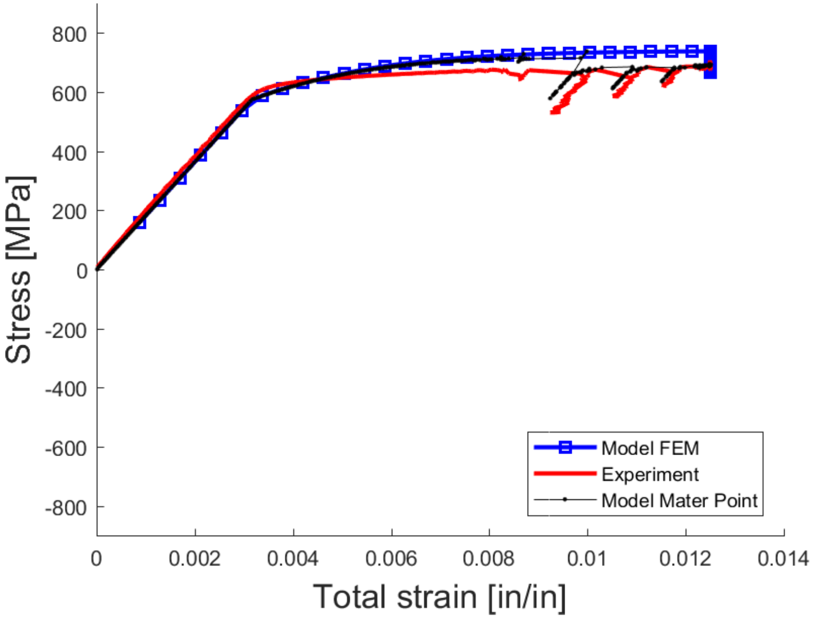

SPLCF, 1100°F
1.2% imposed strain
4h hold time

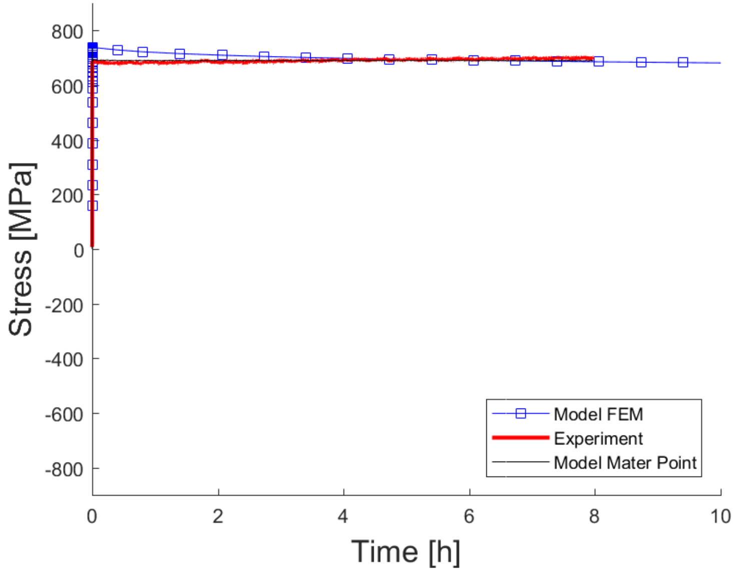


# Model Predictions and Experiments

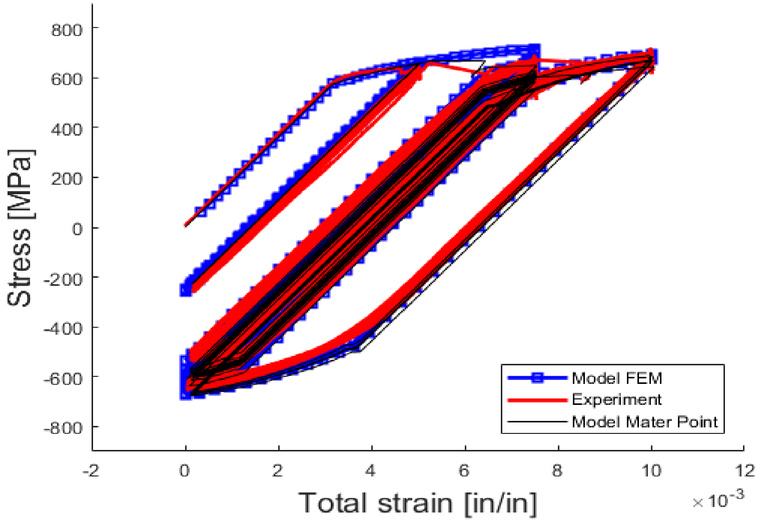
Relaxation
1100ºF
1.2% imposed strain

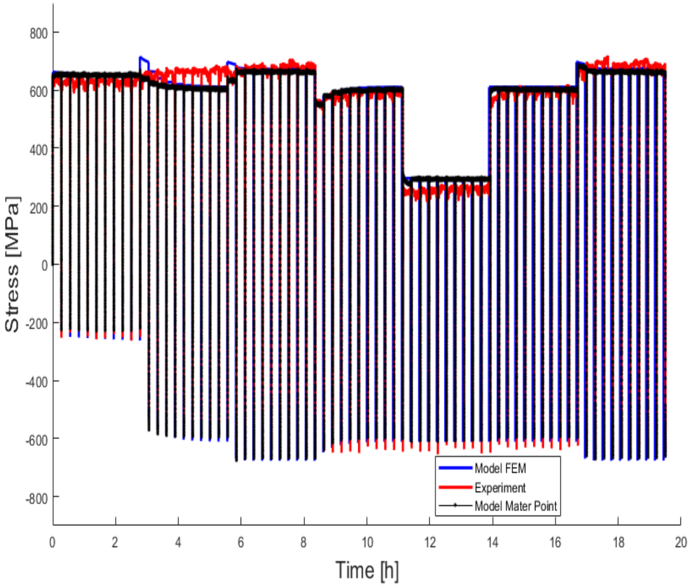



Model – FEM
Model – Material Point
Experiment

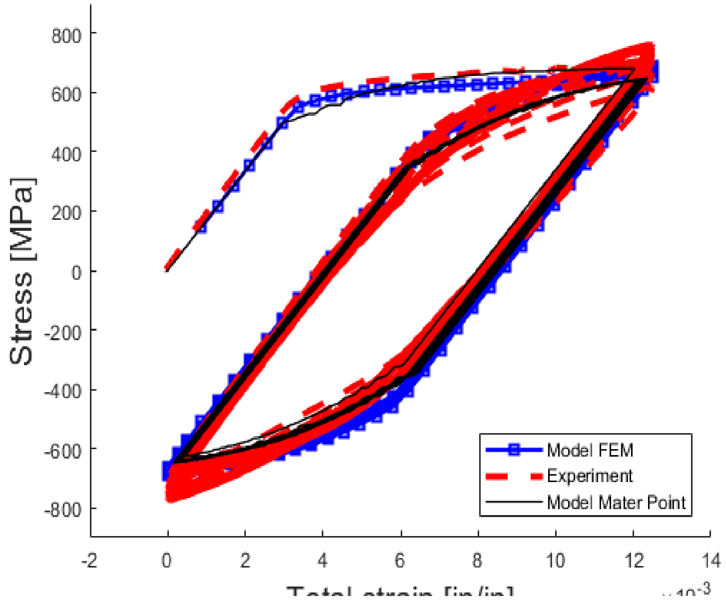
Complex loading 1100ºF
0.5%, 0.7% and 1%
alternating strain amplitudes

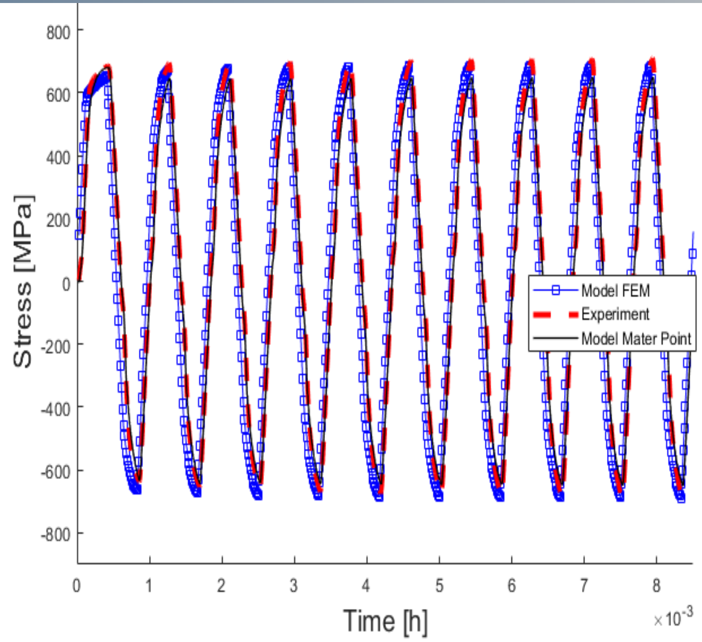


# Model Predictions and Experiments

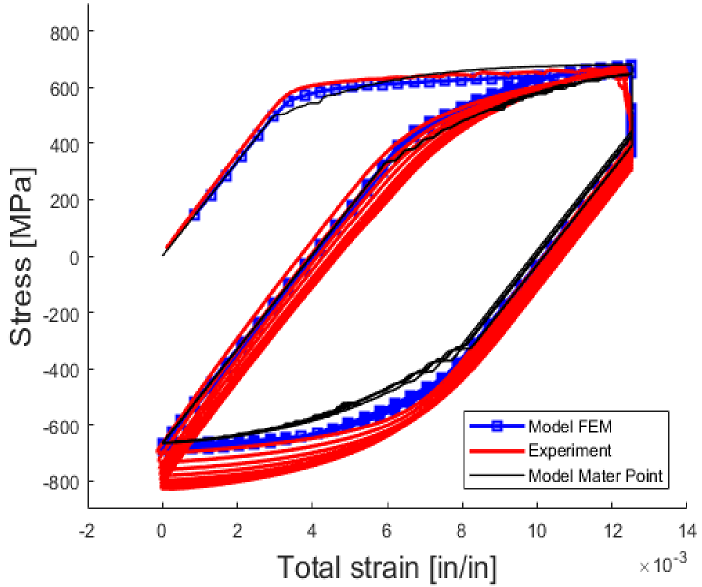
LCF, 1400°F
1.2% imposed strain
20cmp

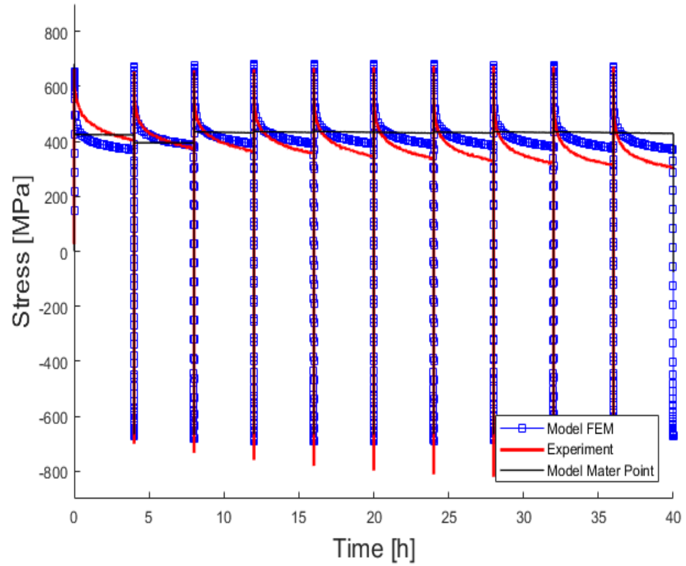



Model – FEM
Model – Material Point
Experiment

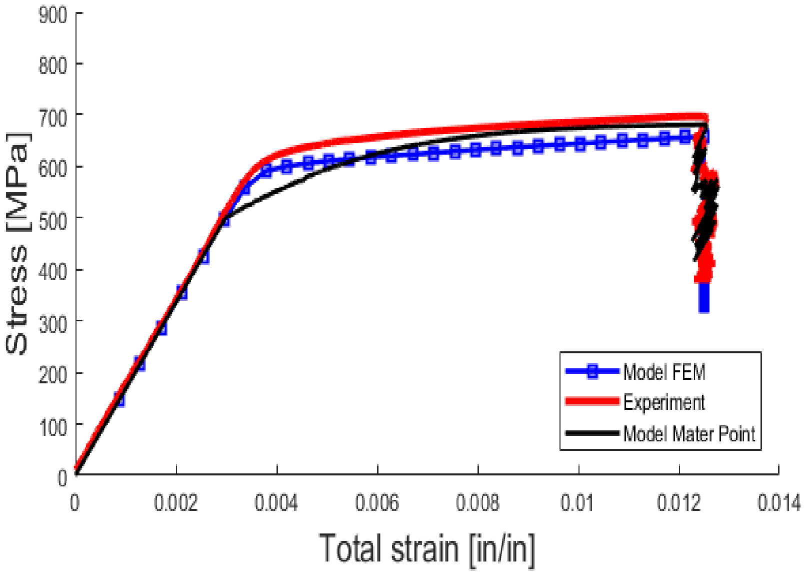
SPLCF, 1400°F
1.2% imposed strain
4h hold time

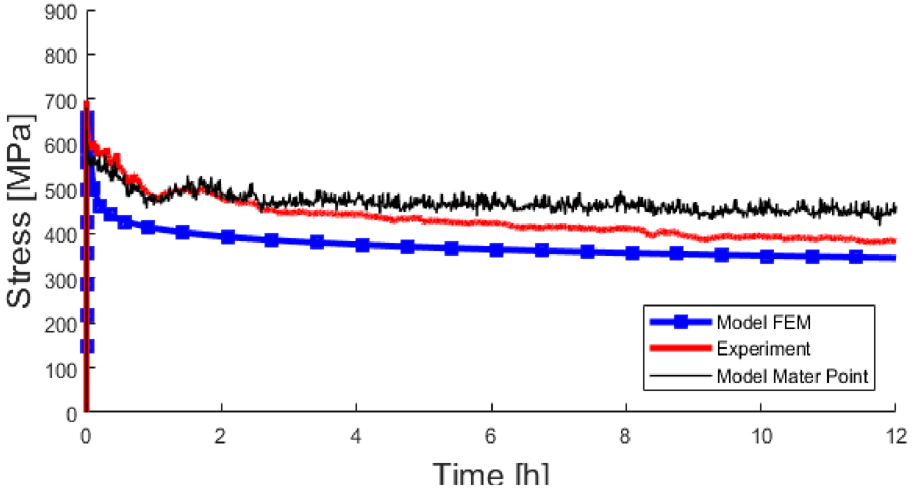


# Model Predictions and Experiments

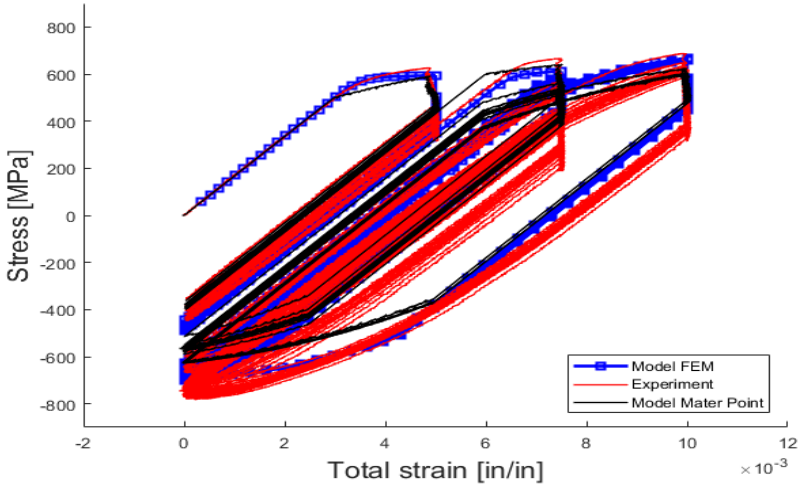
Relaxation 1400ºF
1.2% imposed strain

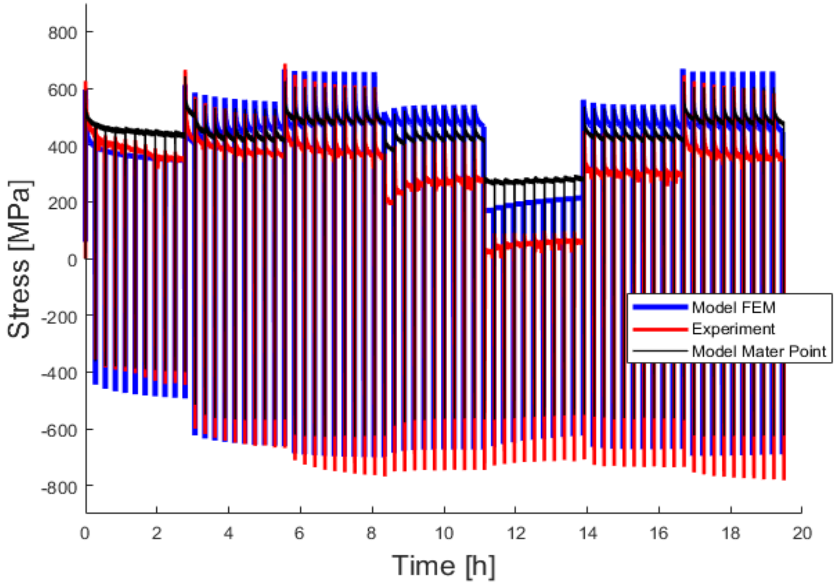


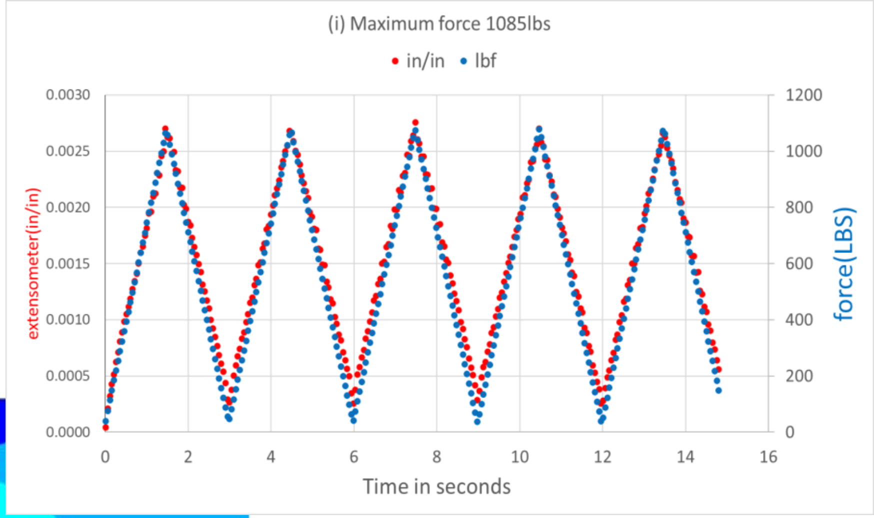

Model – FEM
Model – Material Point
Experiment

Complex loading
1400ºF
0.5%, 0.7% and 1% alternating strain amplitudes

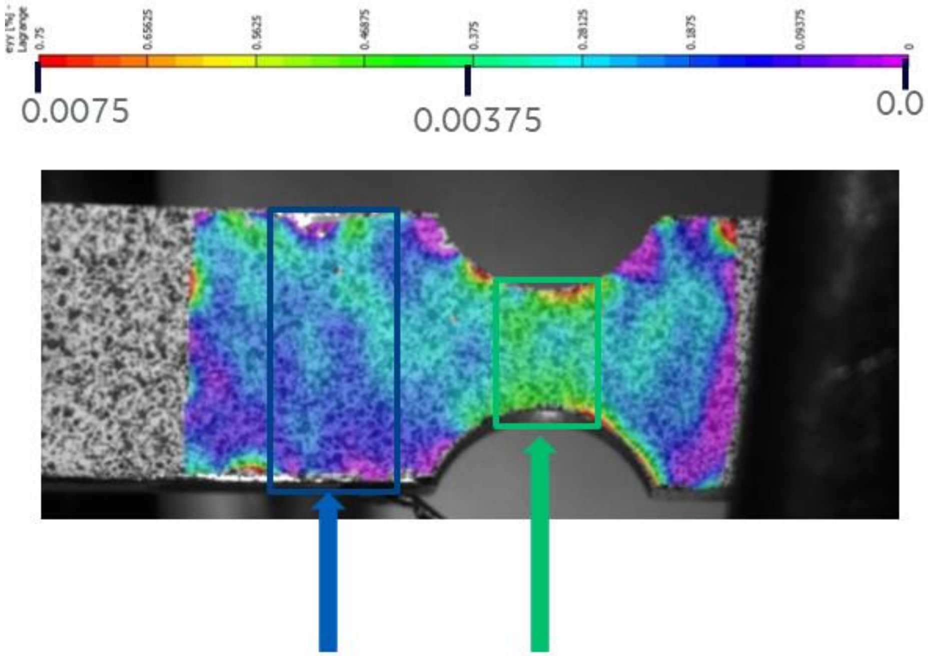


Local strain measurements are currently being performed for model validation

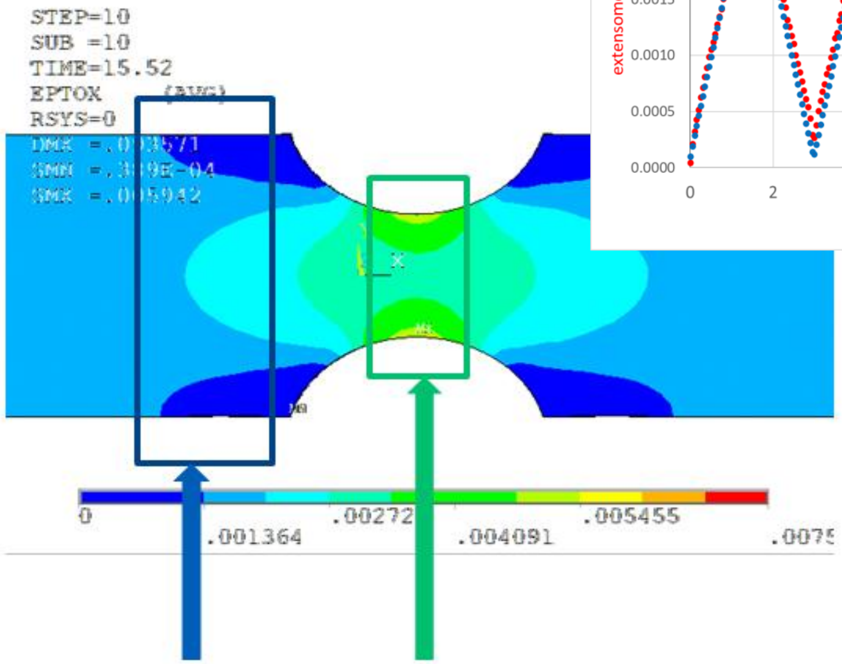



1085Lbf Load




Average =0.221%    Average =0.379%

a) Experiment

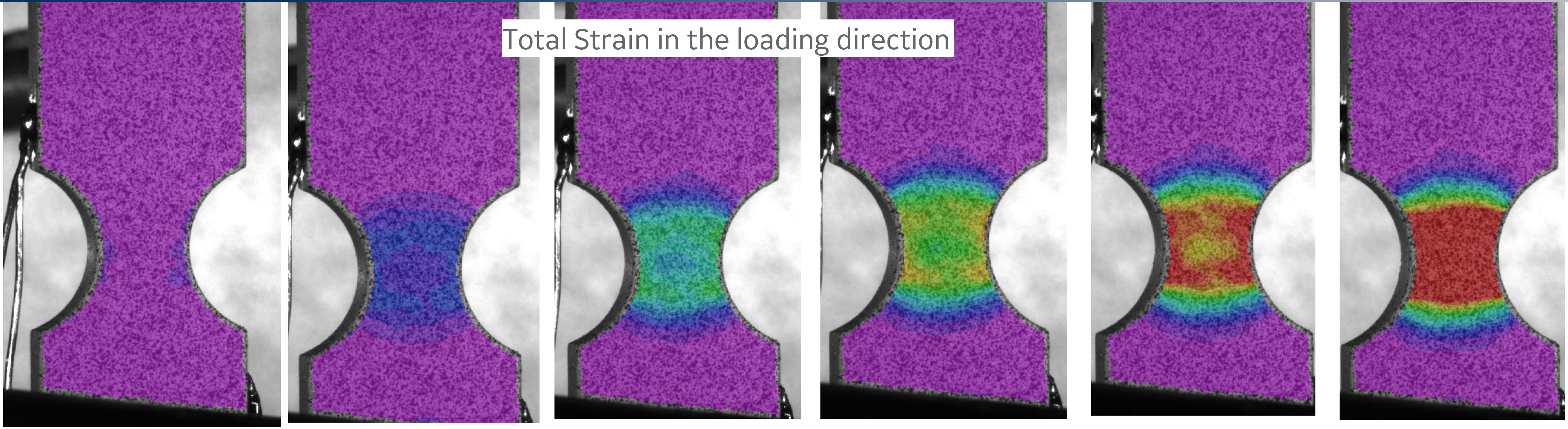



Average =0.167%    Average =0.386%

b) Model

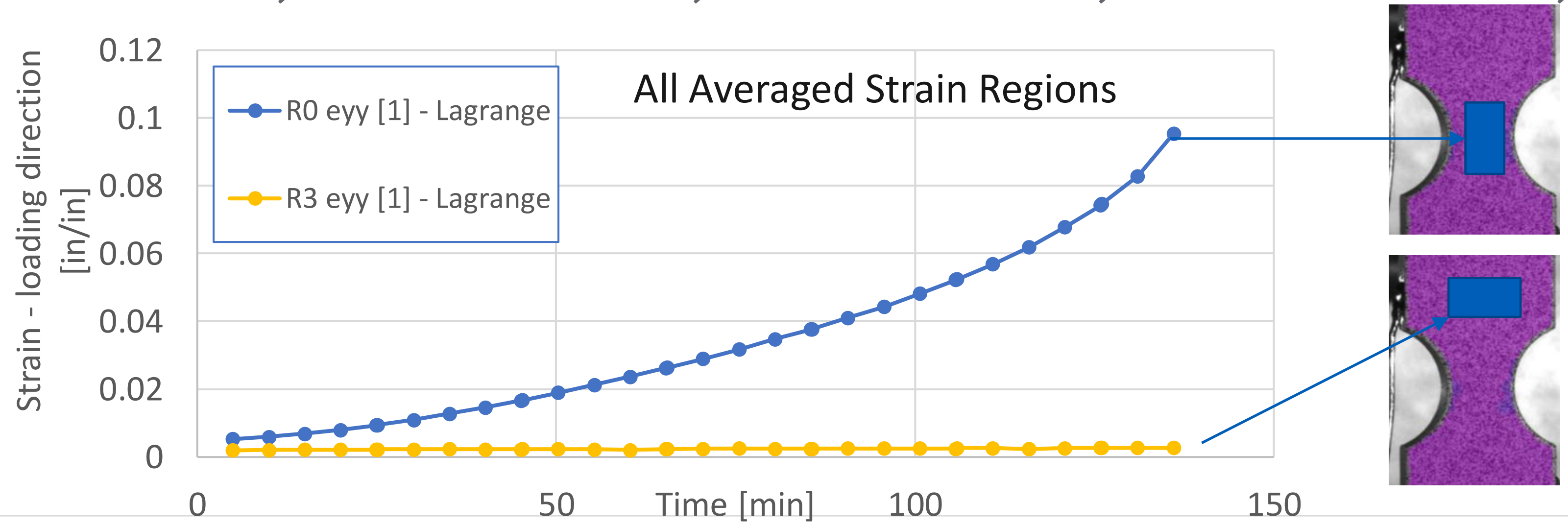
The strain distribution in the loading direction around the notch at about 1085Lbf applied force. 5th cycle

# Model Predictions and Experiments




5 min cycle 1 | 45min (cycle 2) | 85 min (cycle 3) | 110min (cycle 4) | 126min (cycle 5) | 136min (cycle 5)

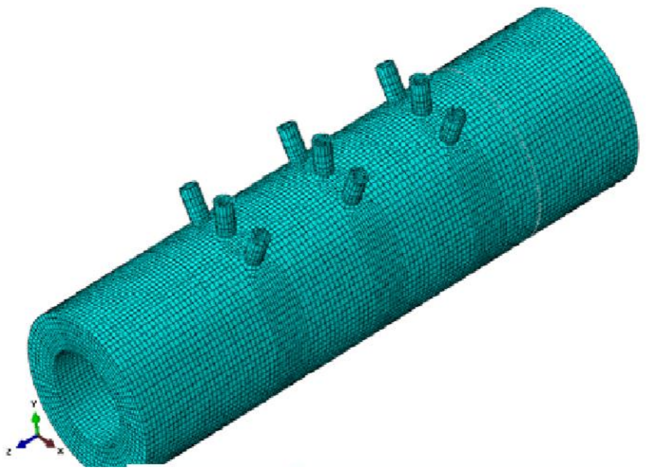
1195Lbf applied force
30min hold time at peak load

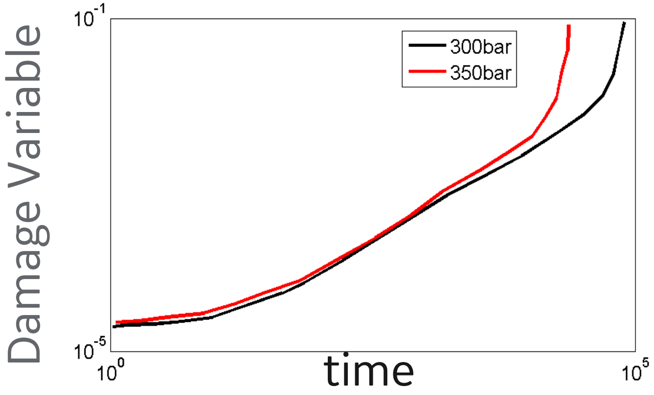


- **Perform Baseline CDM Analyses of a Thick Wall Boiler Component**

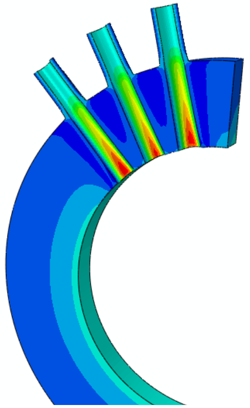
  1100F (USC conditions) - benchmark configuration = Steel outlet header
  1400F (AUSC conditions) –H282 alloy header (newly developed model)

- **Perform Damage Sensitivity Studies on a Thick Wall Boiler Component**






Damage variable evolution and time/cycles to failure in high strain location



# Concluding Remarks

- Performed  mechanical uniaxial tests for deformation mechanisms understanding, model development and calibration for Haynes 282 alloy (tensile, LCF, SPLCF, Relaxation, TMF). Minimum stress relaxation and rate effects at 1100F. Significant creep rates at 1400F.
- Characterized tested specimens for key damage mechanisms identification (TEM, EBSD, SEM), measured dislocation density on deformed specimens.
- 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

**Next Steps**

- Complete model validation on multiaxial stress tests (using local strain measurements)
- Perform  analysis of a thick wall boiler header – Baseline configuration
- Perform damage sensitivity studies on a thick wall boiler header