Environmentally Assisted Fatigue: Experiment & Mechanistic Modeling for Light Water Reactor Sustainability (LWRS) Program

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Objective
Objective:

ANL is trying to develop an experiment-mechanistic framework for life estimation of reactor components under thermal-mechanical cycles and reactor environment.

→ Develop mechanistic finite element model that can be used for improving fatigue life prediction accuracy in reactor components.

→ Perform tensile & fatigue test of various reactor material for generation of basic material properties and validation of FE models.
Baseline System/Component Level FE Model for Stress Analysis
System/Component Level FE Model

Why system/Component level FE model?
- To model multi-axial stress
- To model system level displacement/strain due to thermal-mechanical cycle
- To locate the fatigue hotspots and associated stress/strain history

Present FE model framework

System level FE model

Elastic material properties
Cyclic heat transfer analysis

Cyclic thermal-structural analysis

Example RPV/HL loading boundary condition

System level FE model

FE mesh
Example Heat Transfer Analysis Results

ID surface temperature distribution at the end of 1900 sec

OD surface temperature distribution at the end of 1900 sec

ID and OD surface temperature history at two typical nodes of hot leg
Example Elastic Thermal-Structural Analysis Results

Displacement (magnitude) variation at the end of 1900 sec from stress analysis models with (a) pressure loading, (b) thermal loading, and (c) both pressure and thermal loading.

Maximum displacement time histories at a typical ID node in HL (near SG nozzle).
Nodal displacement (magnitude) animation
Example Elastic Thermal-Structural Analysis Results (Contd.)

**Maximum principal stress** distribution at the end of 1900 sec (at peak temp & pressure) from stress analysis models with (a) pressure loading, (b) thermal loading, and (c) both pressure and thermal loading.

Maximum/minimum principal stress time histories at a typical ID element in the HL elbow from stress analysis models with a) pressure loading, b) thermal loading, c) and both pressure and thermal loading.
Von Mises stress animation

$\sigma_{\text{Von Mises}}$
(Avg: 75%)

+4.400e+02
+3.667e+02
+2.933e+02
+2.200e+02
+1.467e+02
+7.333e+01
+4.578e-05
-7.333e+01
-1.467e+02
-2.200e+02
-2.933e+02
-3.667e+02
-4.400e+02
Fatigue Life Estimation Based on ASME/NUREG-6909 Approach
Example Estimated Fatigue Life

ASME/NUREG-6909 approach for fatigue life

\[ N_{PWR} = \frac{N_{air}}{F_{en}} \]

\[ F_{en} = \exp(-\theta'O'\dot{\varepsilon'}) \]

In-air and environmental fatigue lives estimated under different loading conditions for cold leg

<table>
<thead>
<tr>
<th></th>
<th>Cold leg (based on elbow stress/strain)</th>
<th>Only pressure</th>
<th>Only temperature</th>
<th>Both temperature and pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. stress amplitude (MPa)</td>
<td>27.685</td>
<td>180.87</td>
<td>171.18</td>
<td></td>
</tr>
<tr>
<td>(with elastic modulus correction)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. strain amplitude (%)</td>
<td>0.01662</td>
<td>0.11086</td>
<td>0.10481</td>
<td></td>
</tr>
<tr>
<td>Max. strain rate (%/s)</td>
<td>8.0102e-06</td>
<td>5.3429e-05</td>
<td>5.0512e-05</td>
<td></td>
</tr>
<tr>
<td>In-air fatigue life</td>
<td>&gt;10^6</td>
<td>1.1x10^5</td>
<td>1.9x10^5</td>
<td></td>
</tr>
<tr>
<td>( F_{en} )</td>
<td>1</td>
<td>7.8124</td>
<td>7.8124</td>
<td></td>
</tr>
<tr>
<td>PWR environ. fatigue life</td>
<td>&gt;10^6</td>
<td>14,080</td>
<td>24,320</td>
<td></td>
</tr>
</tbody>
</table>
Cyclic Plasticity Material Models: Theoretical Background
Theoretical background: conventional FE model

**Elastic Analysis**

- Monotonic tensile test data
- Material properties:
  a) Elastic modulus
  b) Poisson’s ratio
- FE model

**Elastic-plastic Analysis**

- Monotonic tensile test data or Cyclic test ½ life data
- Material properties:
  a) Elastic modulus
  b) Poisson’s ratio
  c) Time-independent → Yield stress → Hardening properties
- FE model
Theoretical background: evolutionary material model

Why evolutionary material model?

Material harden/soften as function of accumulated plastic strain or time leading to yield surface expansion/contraction & translation in stress space.

Example: Stress-strain under cyclic loading

Example cyclic hardening under PWR water (316 SS)

How to model this through FE: Should we provide thousands of stress-strain curve as input to FE code?
Evolutionary material model (Contd.)

(i)_th cycle equivalent monotonic stress-strain curve

Linear mapping of hardening stress

Elastic modulus

Given strain

σ_i^y - σ_0^y = increase in cyclic yield stress
= isotropic hardening stress

α_i = Within cycle (beyond yield stress)
kinematic hardening or back stress

Tensile or first quarter cycle (i=0) equivalent monotonic stress-strain curve

Original yield surface (Von-Mises yield function)

Cyclic load: Yield function shifts due to
- Within the cycle stress increase or decrease (kinematic hardening model)

&

Cyclic load: Yield function expands or contracts due to
- Inter-cycle yield stress increase or decrease (isotropic hardening model)

Tensile load: yield function expands or contracts due to
- Monotonic stress increase/ decrease (isotropic hardening model)
Evolutionary material model (Contd.)

Evolutionary von-mises yield criteria for multi-axial FE modeling

\[ f(\sigma_i^j - \alpha_i^i) = \sigma_i^y \]

Stress at \((j)_{th}\) instance of \((i)_{th}\) fatigue cycle

Back stress at \((j)_{th}\) instance of \((i)_{th}\) fatigue cycle

Yield stress of \((i)_{th}\) fatigue cycle

Inter-cycle cyclic yield stress shift (isotropic hardening model)

\(\Rightarrow\) Can directly be modeled through feeding cyclic yield stress ~ accumulated plastic strain to FE code

Within the cycle stress-strain model (kinematic hardening model)

\[ d\alpha_i^j = \frac{2}{3} C_i^{av}(p)d\varepsilon^{pl} \leftarrow \text{Linear model} \]

\[ d\alpha_i^j = \frac{2}{3} C_i^{av}(p)d\varepsilon^{pl} - \gamma_i^{av}(p)\alpha_i^j\bar{p} \leftarrow \text{Nonlinear model} \]
Material, Specimen & Test Setup
Types of material being tested

1. 316SS base
2. 508LAS base
3. 316SS-316SS pure weld
4. 508LAS-316SS filler weld
5. 508LAS-316SS butter weld

Example 316SS-316SS pure weld specimen
Test Setup

In-air test frame

Environmental test frame with PWR water loop and autoclave

Example in-air test thermocouple readings during heat up procedures

Example water pressure during a PWR water test
508 LAS Base & HAZ Metal Tensile Test & Material Model Results
508 LAS Tensile Test & Material Model Results

Example TC profile during entire test

Example thermal strain during stress-free heat up procedure

Substantial strain can generate large stress (beyond yield stress) depending on the constraints and boundary condition of reactor components

508 LAS base & HAZ metal (Engineering) stress-strain curve
508 LAS Tensile Test **Material Model Results** (contd.)

(HAZ metal, 300 °C tensile test: nonlinear kinematic hardening model with 0.2% offset yield stress)

Parameters w.r.t optimization iteration no.

Model estimated stress-strain curve w.r.t experiment stress-strain curve

Parameters w.r.t optimization iteration no.
508 LAS Base Metal Fatigue Test & Material Model Results
Fatigue lives under different conditions (approx. 0.1%/S strain rate)

Cyclic stress hardening/softening observed

requires time-dependent kinematic and isotropic hardening/softening modeling
Example equivalent stress-strain curve for first 50 cycles

Evolution of 0.05% yield stress

Last cycle no. = 2875
Evolution of $C_1$ under different conditions

Evolution of $\gamma_1$ under different conditions

Nonlin. hard parameter: $C_{1y}$ (MPa)

RT-F23 (22 °C, In-air)
ET-F24 (300 °C, In-air)
EN-F20 (300 °C, PWR water)

Nonlin. hard parameter: $\gamma_{1y}$

RT-F23 (22 °C, In-air)
ET-F24 (300 °C, In-air)
EN-F20 (300 °C, PWR water)
316 SS – 316 SS **Weld Tensile Test & Material Model Results**
316 SS – 316 SS Weld Tensile Test & Material Model Results

Example thermal strain during stress-free heat up procedure

![Graph showing thermal strain during stress-free heat up procedure.]

316 SS – 316 SS Weld (Engineering) stress-strain curve

![Graph showing stress-strain curve for 316 SS – 316 SS Weld.]

T03 (316SS-316SS Weld, 22 °C, 0.1%/S)
T05 (316SS-316SS Weld, 300 °C, 0.1%/S)
316 SS – 316 SS Weld Tensile Test Material Model Results (contd.)

(316 SS – 316 SS Weld, 300 °C tensile test nonlinear kinematic hardening model results with 0.2% offset yield stress)

Model estimated stress-strain curve w.r.t experiment stress-strain curve (for T05 tensile test data)
316 SS – 316 SS Weld Fatigue Test & Material Model Results
316 SS – 316 SS Weld Metal Fatigue Test & Material Model Results

Fatigue lives under different conditions

Cyclic stress hardening/softening observed requires time-dependent kinematic and isotropic hardening/softening modeling
316 SS – 316 SS Weld Metal Fatigue Test & Material Model Results (Contd.)

(Example case: 300 °C PWR water fatigue test results)

Example equivalent stress-strain curve for first 50 cycles

Evolution of 0.05% yield stress

Substantial cyclic reduction in yield stress
316 SS – 316 SS Weld Metal Fatigue Test & Material Model Results (Contd.)

(Example case: 300 °C PWR water fatigue test results-contd.)

Evolution of nonlinear kinematic hard.
Parameter C1

Evolution of nonlinear kinematic hard.
Parameter γ1
0.05% offset yield stress evolution under different conditions

Elastic modulus evolution under different conditions

Offset ($\varepsilon_{\text{yl}} = 0.05\%$) yield stress (MPa)

- RT-F08 (22 °C, In-air)
- ET-F07 (300 °C, In-air)
- ET-F17 (300 °C, In-air)
- EN-F18 (300 °C, PWR water)

Elastic modulus (GPa)

- RT-F08 (22 °C, In-air)
- ET-F07 (300 °C, In-air)
- ET-F17 (300 °C, In-air)
- EN-F18 (300 °C, PWR water)
Evolution of nonlinear kinematic hard. parameter $C_1$ under different conditions

Evolution of nonlinear kinematic hard. parameter $\gamma_1$ under different conditions

RT-F08 (22 ºC, In-air)  
ET-F07 (300 ºC, In-air)  
ET-F17 (300 ºC, In-air)  
EN-F18 (300 ºC, PWR water)
Summary
Summary

During FY-15 following works performed:

- A system level baseline FE model developed for cyclic thermal-mechanical stress analysis of a PWR type reactor.

- Tensile & fatigue test conducted under different conditions using 508 LAS base metal specimens.

- Tensile & fatigue test conducted under different conditions using 316 SS-316 SS weld metal specimens.

- Based on the tensile and fatigue test data of 508 LAS & 316 SS-316 SS weld specimens various material properties (both tensile test based time-independent & fatigue test based time-dependent properties) estimated.

Future Direction

- Use of estimated material parameters for component & system level FE model.

- Tensile, fatigue test & material model for other material (e.g. 508LAS-316SS dissimilar metal weld).

- Fatigue test under variable/random load and material modelling.

- Study the effect of stress versus strain control test on material model results.

- Fatigue test and material modeling to study the effect of different hold time under PWR water.
Thank You