A Guideline for the Assessment of Uniaxial Creep and Creep-Fatigue Data and Models

Student Researcher : Md Abir Hossain
PI : Dr. Calvin M Stewart
Co-PI : Dr. Jack Chessa
Outline

• Project Objective
• Motivation
• The Team
• Systematic Approach to Assessment
  • Project Task
  • Project Milestone
• List of Publications
• Ongoing Works
  • Modified Wilshire Model
  • Modified Theta Projection Model
  • Metamodeling
  • Probabilistic Creep Modeling
• Result and Accomplishment
• Future Work
• Market benefits/Assessment
• Conclusion
• Of primary concern to FE practitioners is a determination of which constitutive models are the “best”, capable of reproducing the mechanisms expected in an intended design accurately; as well as what experimental datasets are proper or “best” to use for fitting the constitutive parameters needed for the model(s) of interest.

RO1

Development of Aggregated Experimental Databases of Creep and Creep-Fatigue Data

RO2

Computational Validation and Assessment of Creep and Creep-Fatigue Constitutive Models for Standard and Non-Standard Loading Conditions
Recent drives to increase the efficiency of existing fossil energy (FE) power plants and the development of Advanced Ultrasupercritical (A-USC) power plants, have led to designs with steam pressures above 4000 psi and temperatures exceeding 1400°F.
Technology Benchmarking

• The existing FE fleet has an **average age of 40 years**.

• The Department of Energy has outlined a strategy of life extension for US coal-fired power plants where many plants will operate for **up to 30 additional years of service**.

In Service Hours….
30 Years = 262,974 hours
40 Years = 350,634 hours
70 Years = 613,607 hours

There is a Need for Improved Creep Prediction Technology

**Uncertainty ↑**
**Temperature ↑**
**Stress ↓**

Creep-Rupture of 9Cr-1Mo Tube

300,000 hours
• An immense number of models have been developed to predict the deformation, damage evolution, and rupture of structural alloys subjected to Creep and Creep-Fatigue.

• Significant amount of research has been done on the creep-rupture model.

• Current research is directed towards Creep viscoplasticity and meta modeling.

• Project focus has shifted from the “Creep and Creep-Fatigue” to just “Creep”
The Team

Alumni

Mohammad Shafinul Haque
Tenure Track Asst. Professor at Angelo State University

Christopher Ramirez
Metallurgy Test Technician at Element

Md Abir Hossain
Ph.D.

Alumni

Dr. Calvin M Stewart, Project PI

Dr. Jack F Chessa, Project Co-PI

Current Members

Jaime Cano
MS

Jimmy J Perez
MS
Signed Offer with Lockheed Martin

Ricardo Vega
MS
Systematic Approach to Assessment

Example for Creep Deformation

Aggregate Datasets with Uncertainty

Analytical Fit

Global Optimization

MACHO

Material Constant Heuristic Optimization

Model Fit to Datasets

Interpolation & Extrapolation

Standard Performance

Nonstandard Performance

Performance

A B C D F

Model Uncertainty

NMSE, Z_{CRMS}
Task 1: Project Management, Planning, and Reporting

Task 2: Locate, Digitize, Sort, and Store Creep-Rupture Data

Task 3: Uncertainty of Creep and Creep-Fatigue Data

Task 4: Mathematical Analysis and FEA of Models

Task 5: Calibration & Validation – Fit, Interpolation, and Extrapolation of Models

Task 6: Post-Audit Validation of the Models

Task 7: Uncertainty Analysis of Models

Task 8: Final Assessment
### Creep Data Thus Far...

<table>
<thead>
<tr>
<th>Source</th>
<th>Creep Deformation</th>
<th>Stress Relaxation</th>
<th>Min. Strain Rate</th>
<th>Time to Cr. Strain</th>
<th>Creep Rupture</th>
<th>Mono. Tensile</th>
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### Alloys:

- P91
- 316SS/N

### Planned:

- 304SS
- IN617
- IN625
- IN718
- ...
Creep Data Work Thus Far…

- **Rupture life**, $t_r$ (hr)
  - 100, 101, 102, 103, 104, 105, 106, 107, 108

- **Stress**, $\sigma$ (MPa)
  - 20, 30, 40, 50, 60, 80, 100

- **Temperature**
  - 550°C, 600°C, 650°C

- **Material types**
  - P91, LM, MS, CD

- **Data cull**
  - 10% data cull from the lowest stress data
  - 50% data cull between $t_r,\text{max}/10$ and the longest experimental time.
List of Publication

• Journal Articles


List of Publication (cont...)

• Conference Papers
• Short Papers


Previous Works
1. A modified Wilshire Model for Creep Deformation, Damage, and Rupture Prediction

2. An Analytical Calibration for a Modified Theta-Projection Model

3. Metamodelling Minimum Creep Strain Rate Laws

4. A Probabilistic Approach to Creep Deformation, Damage, and Rupture Prediction
Biography

• BS in Mechanical Engineering; The University of Texas at El Paso (2014-2018).
• MS in Mechanical Engineering; The University of Texas at El Paso, (Fall 2018-current)
• Graduate Research Assistant at The UTEP Materials at Extreme Research Group (MERG)

List of Publication

Wilshire Model

Stress-Rupture and Minimum-Creep-Strain-Rate Model

\[
\frac{\sigma}{\sigma_{TS}} = \exp(-k_1 \left[ t_f \exp \left( -\frac{Q^*_c}{RT} \right) \right]^u)
\]

\[
\frac{\sigma}{\sigma_{TS}} = \exp(-k_2 \left[ \dot{\varepsilon}_{min} \exp \left( \frac{Q^*_c}{RT} \right) \right]^v)
\]
Continuum Damage Mechanics (CDM) Framework

Insertion of Wilshire Model into Sinh CDM Model

Sine-Hyperbolic (Sinh) Framework

\[ \dot{\varepsilon}_{cr} = \dot{\varepsilon}_{min} \exp(\lambda \omega^{3/2}) \]

\[ \dot{\varepsilon}_{min} = \frac{-\ln\left(\frac{\sigma}{\sigma_{TS}}\right)}{k_2} \frac{1}{\nu} \exp\left(\frac{Q_c^*}{RT}\right) \]

Minimum-creep-strain-rate

\[ \omega(t) = -\frac{1}{\phi} \ln\left[1 - \left[1 - \exp(\phi)\right] \frac{t}{t_r}\right] \]

Damage Model

Wilshire Model Framework

\[ t_r = \frac{-\ln\left(\frac{\sigma}{\sigma_{TS}}\right)}{k_1} \frac{1}{\bar{u}} \exp\left(-\frac{Q_c^*}{RT}\right) \]

Time of Rupture
- The previous model proposed to create creep deformation curves that is not clear and is complicated to implement.
- The modified Wilshire model has a clear analytical approach that depends on the equations already established.
- The rupture predictions of the model enables the capabilities of the modified model to predict ductility even for long-term data.
- The model predicts with high accuracy for P91 and 304 stainless steel even with uncertainty in the data.
- If enough data is given, the model has the capability to predict across multiple isotherms and stress levels due to the nature of the Wilshire model.
Biography

- MS in Mechanical Engineering; The University of Texas at El Paso, (Fall 2018-current)
- Graduate Research Assistant at The UTEP Materials at Extreme Research Group (MERG)

List of Publication

A new analytical method of calibration Theta-Projection model is proposed. The traditional method proposed by Evans requires the constants to be calibrated using a least-square nonlinear scheme of numerical optimization with respect to an error function. This results in constant values with no physical significance, which in turn does not provide a consistent trend for long-term prediction. The analytical method derives the theta constants from test data to give the constants physical realism.

The accumulated primary strain is equated to $\theta_1$ and is used to back-solve for $\theta_2$.

The tertiary acceleration is determined by taking the quotient of the second derivative over the first derivative at 95% of rupture time and is used to back-solve for $\theta_3$. 

### Primary equation

$$\varepsilon_{pr} = \theta_1 (1 - \exp(-\theta_2 t))$$

### Tertiary equation

$$\varepsilon_{tr} = \theta_3 (\exp(\theta_4 t_{exp}) - 1)$$

Theta-Projection model

$$\varepsilon = \theta_1 (1 - \exp(-\theta_2 t)) + \theta_3 (\exp(\theta_4 t) - 1)$$
Modified Interpolation/Extrapolation Functions

The original interpolation/extrapolation function used with the Thera-projection model does not consistently provide good predictions with limited data. A much more consistent trend with rupture time is proposed for prediction. The error between the new function and the calibrated theta constants is less than that of the original. A benefit to the alternative prediction function is that it requires less variables than the original.

<table>
<thead>
<tr>
<th></th>
<th>$\theta_1$ NMSE</th>
<th>$\theta_2$ NMSE</th>
<th>$\theta_3$ NMSE</th>
<th>$\theta_4$ NMSE</th>
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<tbody>
<tr>
<td>Alternative function</td>
<td>0.0190</td>
<td>4.9527e-4</td>
<td>0.0921</td>
<td>2.2936e-3</td>
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<td>Original function</td>
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<td>9.2036e-4</td>
<td>0.0855</td>
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<td>% Improvement</td>
<td>12</td>
<td>85</td>
<td>7</td>
<td>131</td>
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Rupture Predictions for New Function

The Modified interpolation/extrapolation function requires a method to predict rupture time. The Wilshire model provides an equation to predict rupture time that relies on the temperature and stress of test data as well as activation energy for the material. The Wilshire model also serves as analytical means to predict rupture time rather than using an arbitrary average rupture ductility to find rupture time using the theta model.

Wilshire Equation

\[
\frac{\sigma}{\sigma_{TS}} = \exp(-k_1 \left[ t_r \exp\left(-\frac{Q^*}{RT}\right) \right]^u)
\]

Rearranged to relate experimental stress and temperature to rupture time

\[
t_r = \frac{1}{\exp\left(-\frac{Q^*}{RT}\right) - k_1} \left(\ln\left(\frac{\sigma}{\sigma_{TS}}\right)\right)^{1/u}
\]

Material constants \(k_1, k_2, u,\) and \(v\) are calibrated using several stresses at various isotherms to predict rupture time.

Rupture predictions using the Wilshire equation are compared to calibration data and validation data for a single isotherm of alloy P91.

<table>
<thead>
<tr>
<th>Constant</th>
<th>Plate</th>
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<tbody>
<tr>
<td>(Q_{av}^*) (kJ/mol)</td>
<td>290</td>
</tr>
<tr>
<td>(k_1) (hr(^{-1}))</td>
<td>98.36</td>
</tr>
<tr>
<td>(u) (unitless)</td>
<td>0.1441</td>
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<tr>
<td>(k_2) (hr(^{-1}))</td>
<td>108.60</td>
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<tr>
<td>(v) (unitless)</td>
<td>-0.1475</td>
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</tbody>
</table>

Stress-Rupture Data

Validation Data

Stress-Rupture Prediction
Metamodeling Minimum-Creep-Strain-Rate Laws

Biography

• B.Sc. in Mechanical Engineering; University of Texas at El Paso, (2015-2018).
• M.S. in Mechanical Engineering; The University of Texas at El Paso, (Spring 2019-Current)
• Masters Research Assistant at The UTEP Materials at Extreme Research Group (MERG)

List of Publication

Metamodeling is the process of applying mathematical rules and constraints to generate models-of-models. These models-of-models, or “metamodels”, exist as a mathematical combination of known models that can regress back into each known model under prescribed constraints.

- Metamodel has the capability for the self identification for a given set of data.
- Metamodels can be employed in an unconstrained or pseudo-constrained manner to identify unique MCR models that exist between the known models.
<table>
<thead>
<tr>
<th>Model</th>
<th>Equation</th>
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<tbody>
<tr>
<td>Norton 1929</td>
<td>( \dot{\varepsilon}_{\text{min}} = A \left( \frac{\sigma}{\sigma_0} \right)^n \exp \left( -\frac{Q_c}{RT} \right) )</td>
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<tr>
<td>Simplified Norton 1929</td>
<td>( \dot{\varepsilon}_{\text{min}} = A \sigma^n \exp \left( -\frac{Q_c}{RT} \right) )</td>
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<tr>
<td>Nadai 1931</td>
<td>( \dot{\varepsilon}_{\text{min}} = A \exp \left( \frac{1}{\sigma_0} \right) \exp \left( -\frac{Q_c}{RT} \right) )</td>
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<td>Soderberg 1936</td>
<td>( \dot{\varepsilon}_{\text{min}} = A \exp \left( \frac{\sigma}{\sigma_0} \right) \exp \left( -\frac{Q_c}{RT} \right) )</td>
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<td>McVetetty 1943</td>
<td>( \dot{\varepsilon}_{\text{min}} = A \sinh \left( \frac{\sigma}{\sigma_0} \right) \exp \left( -\frac{Q_c}{RT} \right) )</td>
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<td>Dorn 1955</td>
<td>( \dot{\varepsilon}_{\text{min}} = A \exp \left( \frac{\sigma}{\sigma_0} \right) \exp \left( -\frac{Q_c}{RT} \right) )</td>
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<td>Johnson-Henderson-Kahn 1936</td>
<td>( \dot{\varepsilon}_{\text{min}} = \left[ A_1 \left( \frac{\sigma}{\sigma_0} \right)^{n_1} + A_2 \left( \frac{\sigma}{\sigma_0} \right)^{n_2} \right] \exp \left( -\frac{Q_c}{RT} \right) )</td>
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<td>Garofalo 1965</td>
<td>( \dot{\varepsilon}_{\text{min}} = A \sinh \left( \frac{\sigma}{\sigma_0} \right) \exp \left( -\frac{Q_c}{RT} \right) )</td>
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<td>Wilshire 2007</td>
<td>( \dot{\varepsilon}<em>{\text{min}} = \left[ -\ln \left( \frac{\sigma}{\sigma</em>{TS}} \right) \right]^{\frac{1}{k_2}} \exp \left( -\frac{Q_c}{RT} \right) )</td>
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Proposed MCR Metamodel

- **Metamodel (Constrained)**
  \[
  \dot{\varepsilon}_{\text{min}} = A_1 \left( \frac{\sigma}{\sigma_o} \right)^{n_1} + A_2 \left( \frac{\sigma}{\sigma_o} \right)^{n_2} + A_3 \sinh \left( \frac{\sigma}{\sigma_o} \right)^{n_3} + A_4 \exp \left\{ \left( \frac{\sigma}{\sigma_o} \right) - \alpha_o \right\}
  \]

- **Metamodel (Pseudo-Constrained)**
  \[
  \dot{\varepsilon}_{\text{min}} = H(x_1) A_1 \left( \frac{\sigma}{\sigma_o} \right)^{n_1} + H(x_2) A_2 \left( \frac{\sigma}{\sigma_o} \right)^{n_2} + H(x_3) A_3 \sinh \left( \frac{\sigma}{\sigma_o} \right)^{n_3} + H(x_4) A_4 \exp \left\{ \left( \frac{\sigma}{\sigma_o} \right) - H(x_4) \alpha_o \right\}
  \]

- **Temperature Dependent Metamodel (Constrained)**
  \[
  \dot{\varepsilon}_{\text{min}} = \left[ A_1 \left( \frac{\sigma}{\sigma_o} \right)^{n_1} + A_2 \left( \frac{\sigma}{\sigma_o} \right)^{n_2} + A_3 \sinh \left( \frac{\sigma}{\sigma_o} \right)^{n_3} + A_4 \exp \left( \frac{a_1}{\sigma_o} + c\sigma - a_2 \right) + \left( \frac{a_3 \ln \left( \frac{\sigma}{\sigma_o} \right)}{k_2} \right) \right]^{\frac{1}{v}} \times \exp \left( -\frac{Q}{RT} \right)
  \]
MCR Prediction for Different Models

Norton

Simplified Norton

Dorn

Soderberg

McVetty

Garofalo

Stress, $\sigma$ (MPa)

MCR, $\frac{\sigma}{\tau_{\text{min}}}$ (hr$^{-1}$)

Stress, $\sigma$ (MPa)

MCR, $\frac{\sigma}{\tau_{\text{min}}}$ (hr$^{-1}$)

Stress, $\sigma$ (MPa)

MCR, $\frac{\sigma}{\tau_{\text{min}}}$ (hr$^{-1}$)

Stress, $\sigma$ (MPa)

MCR, $\frac{\sigma}{\tau_{\text{min}}}$ (hr$^{-1}$)
Generated Predictions

Stress, $\sigma$ (MPa)

MCR, $\dot{\sigma}_{\text{min}}$ (hr$^{-1}$)

EXP 600°C
EXP 625°C
EXP 650°C
SIM 600°C
SIM 625°C
SIM 650°C

Pseudo-Constrained Isotherm

<table>
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<th>Temp (°C)</th>
<th>NMSE</th>
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<td>625</td>
<td>0.1055</td>
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<td>650</td>
<td>0.0833</td>
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Temp-Dependence

All 6.58

JHK Model, Pseudo-Constrained

JHK Model, Temp Dependence, Constrained
Probabilistic Approach to Creep Modeling

Biography
• B.Sc. in Naval Architecture and Marine Engineering; Bangladesh University of Engineering and Technology, (2011-2016).
• Ph.d. in Mechanical Engineering; The University of Texas at El Paso, (Fall 2018-current)
• Worked as a Lecturer in the Department of Naval Architecture and Marine Engineering in Military Institute of Science of Technology.
• Doctoral Research Assistant at The UTEP Materials at Extreme Research Group (MERG)

List of Publication
Sources of Uncertainty

- The Reliability of Creep Behavior
- Uncertainty of Material Constants
- Uncertainty of pre-existing Defects
- Uncertainty of Service Condition
  \[ \Delta \sigma(t), \Delta T(t) \]
The coupled creep-damage Sinh constitutive model used in this study consisting of creep strain rate and damage evolution equations are as follow

\[ \dot{\varepsilon}_{cr} = A \sinh \left( \frac{\sigma}{\sigma_s} \right) \exp(\lambda \omega^{3/2}) \]

\[ \dot{\omega} = M \left[ 1 - \exp(-\phi) \right] \sinh \left( \frac{\sigma}{\sigma_i} \right)^{\chi} \exp(\phi \omega) \]

<table>
<thead>
<tr>
<th>Material Constant</th>
<th>Behavior</th>
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<tr>
<td>( A )</td>
<td>Secondary Creep coefficient</td>
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<tr>
<td>( M )</td>
<td>Accommodates temperature dependency</td>
</tr>
<tr>
<td>( \sigma_s )</td>
<td>Mechanism Transition Stress</td>
</tr>
<tr>
<td>( \sigma_i )</td>
<td>Mechanism transition stress</td>
</tr>
<tr>
<td>( \phi )</td>
<td>Controls the trajectory</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Dictates the slope of creep curves</td>
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</table>
• Experimental creep deformation data for 304 Stainless Steel with 10 replicated test at each temperature state was adopted from the material database.

• Sine-Hyperbolic creep-damage model has been selected for integrating the probabilistic feature because of the ease of calibration and implementation over other model.

• Different material constant present in the Sinh model were calibrated and demonstrated the intrinsic uncertainty carried by each of the material constant.

• Monte Carlo simulation was used to introduce the randomness into the model.
## Inherent Uncertainty in Experimental Data of 304SS

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Stress</th>
<th>Criteria</th>
<th>Maximum</th>
<th>Minimum</th>
<th>% CoV</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>320</td>
<td>MCSR, %</td>
<td>0.07281</td>
<td>0.029988</td>
<td>34.57</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rupture Time (hr)</td>
<td>63.3608</td>
<td>46.0542</td>
<td>12.55</td>
</tr>
<tr>
<td>300</td>
<td></td>
<td>MCSR, %</td>
<td>0.025743</td>
<td>0.011349</td>
<td>34.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rupture Time (hr)</td>
<td>147.439</td>
<td>100.002</td>
<td>16.12</td>
</tr>
<tr>
<td>650</td>
<td>260</td>
<td>MCSR, %</td>
<td>0.188527</td>
<td>0.108447</td>
<td>23.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rupture Time (hr)</td>
<td>42.1296</td>
<td>26.8894</td>
<td>16.60</td>
</tr>
<tr>
<td>240</td>
<td></td>
<td>MCSR, %</td>
<td>0.46198</td>
<td>0.017676</td>
<td>48.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rupture Time (hr)</td>
<td>163.526</td>
<td>127.615</td>
<td>9.48</td>
</tr>
<tr>
<td>700</td>
<td>180</td>
<td>MCSR, %</td>
<td>0.056326</td>
<td>0.020673</td>
<td>43.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rupture Time (hr)</td>
<td>93.1263</td>
<td>82.7343</td>
<td>4.48</td>
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<tr>
<td>160</td>
<td></td>
<td>MCSR, %</td>
<td>0.008776</td>
<td>0.006251</td>
<td>12.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rupture Time (hr)</td>
<td>196.412</td>
<td>156.9509</td>
<td>8.79</td>
</tr>
</tbody>
</table>
SCRi Model

Start

Input
Calibrated Material Constants

Random Numbers

Uncertainty
$M, \sigma_t$

Rupture
time, $t_{tr}$

Vector of t

Random Numbers

Uncertainty
$A, \sigma_s$

Random Numbers

Uncertainty
$\lambda$ and $\phi$

Random Numbers

Uncertainty
$\omega_o$

Stress Fluctuation

Damage $\omega$, Damage rate $\dot{\omega}$, Creep rate $\dot{\epsilon}$

Creep strain, $\epsilon_{cr}$

Plot $\epsilon_{cr}$ vs t

$n = n + 1$

N is the number of Monte Carlo Simulation

Current: Uniform Distributed Random Numbers

Future: Normal Distributed Random Numbers

End
Predicted Creep Deformation Curves

At 600 °C subjected to 320 MPa

At 600 °C subjected to 300 MPa
Predicted Creep Deformation Curve

At 650 °C subjected to 260 MPa

At 650 °C subjected to 240 MPa
Predicted Creep Deformation Curves

At 700 °C subjected to 180 MPa

At 700 °C subjected to 160 MPa
Reliability Bands for MCSR

MCSR Bands at 600 °C

MCSR Bands at 650 °C

MCSR Bands at 700 °C
Reliability Bands for Stress-Rupture

- Reliability bands represents whether the probabilistic evaluation is conservative or non-conservative.

- Probabilistic feature in creep-damage model will help estimate the failure of the components well in advance.

- Application of Probabilistic evaluation in the Metamodeling will be explored.

- Integration of the probabilistic modeling in the commercial FEM software will help in simulating event which might cause catastrophic failure such as failure of a turbine blade.
Market Benefits/Assessment

• Better prediction for long term service: Aid Design
• Assess the probability of failure.
• Uncertainty calibration: Repair, Replacement, Refurbishment.
• Schedule less inspection: Condition based inspection
• Replacement can be scheduled before the actual failure.
Technology-to-Market Path

• Generalized USER CREEP file for the commercial and academic use.
• Developed material database: scope to add more.
• User Material creep subroutine for the FEM software.
• Optimization of the component material behavior at extreme environment
Concluding Remarks

- Probabilistic Creep Models: Alternative to expensive testing.
- Life prediction: DOE life extension program.
- Inherent Uncertainty: Long lived FE fleets.
- Complete the ongoing and final tasks enlisted in the Project proposal.
- Guideline for the model selection: Best Model; Best Data.
Acknowledgments

Md Abir Hossain
Ph.D. in Mechanical Engineering
Doctoral Research Assistant
mhossain9@miners.utep.edu

Calvin M. Stewart, PhD
Associate Professor of Mechanical engineering
Director of the Materials at Extremes Research Group
cmstewart@utep.edu

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QUESTION