THE UNIVERSITY OF TEXAS AT EL PASO
COLLEGE OF ENGINEERING

2019 Annual Review Meeting for Crosscutting Research

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

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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

Project Objective

- 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

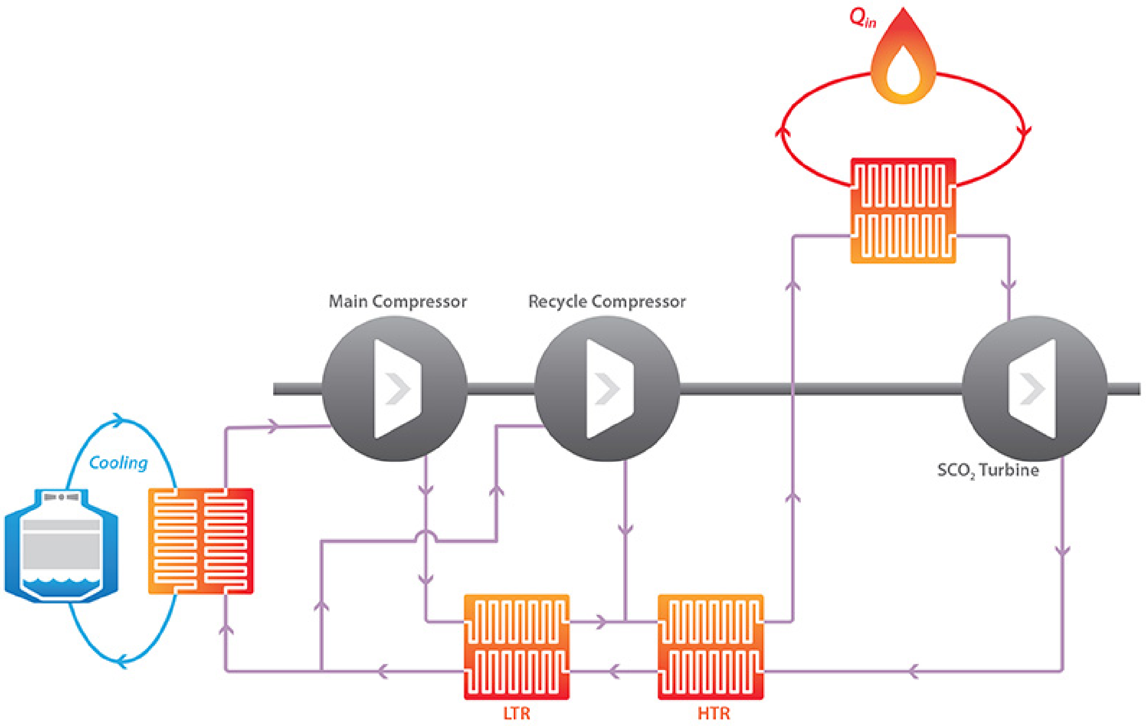
RO2

Computational Validation and Assessment of Creep and Creep-Fatigue Constitutive Models for Standard and Non-Standard Loading Conditions

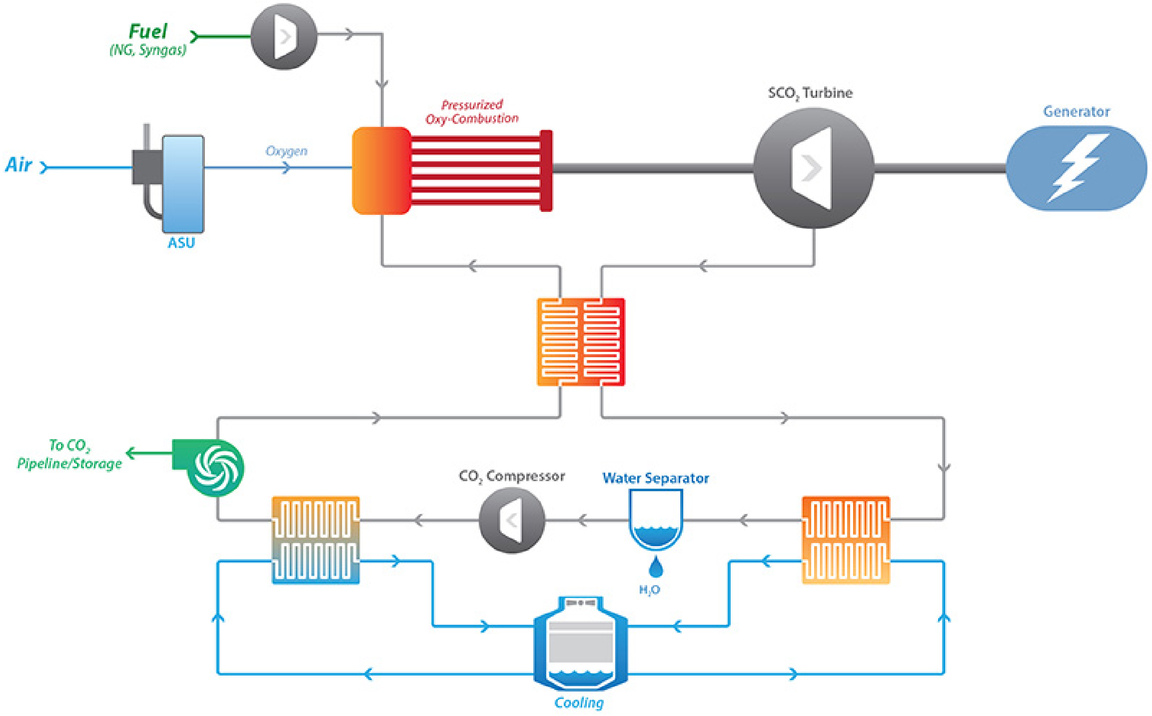
Strategic Alignment and 2018 Goals

Power Plant Efficiency Improvement

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**.



Indirect-Fire Supercritical CO$_2$ Recompression Brayton Cycle



Oxy-Fueled Directly-Fired Supercritical CO$_2$ Cycle

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**.

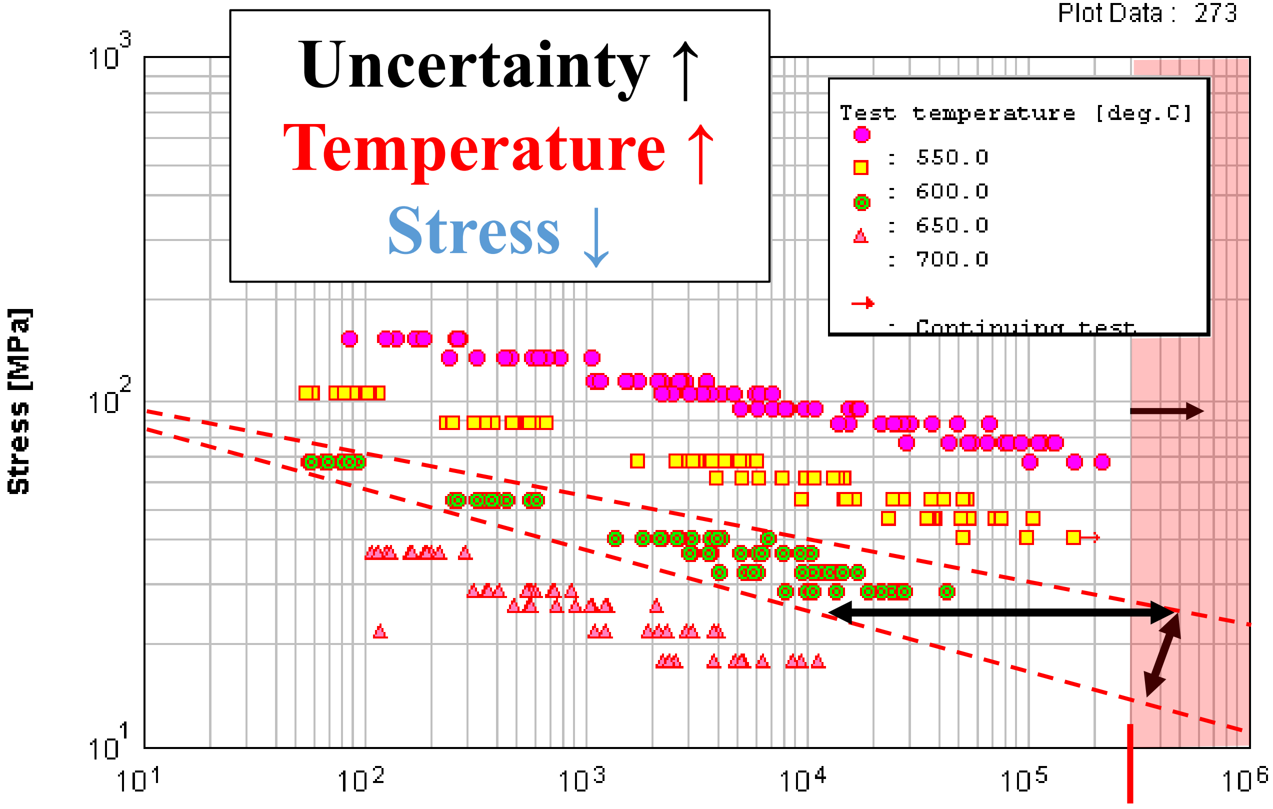
In Service Hours….

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 ↓

300,000 hours

Creep-Rupture of 9Cr-1Mo Tube

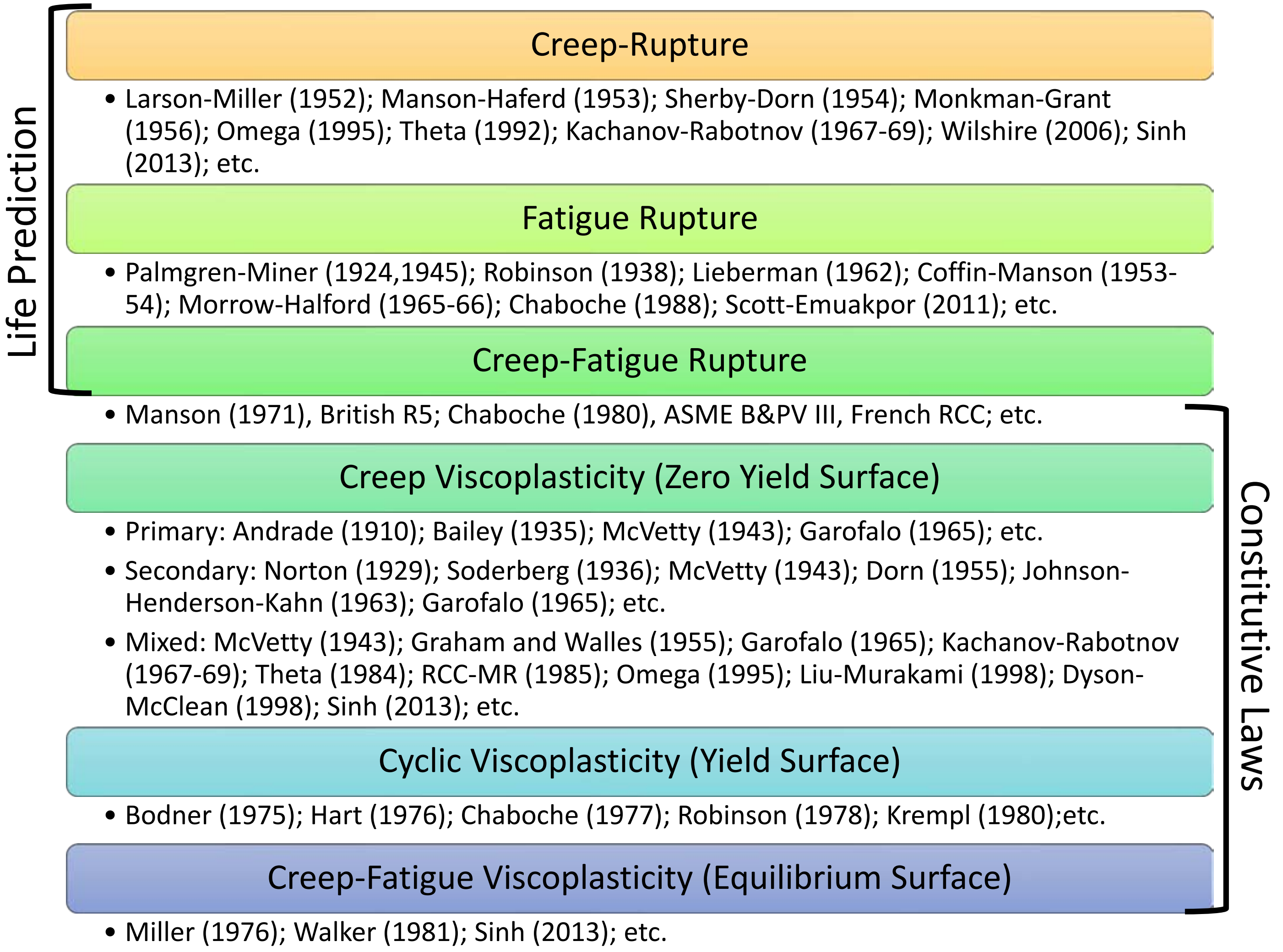
Motivation

- 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"



Life Prediction

Creep-Rupture

- Larson-Miller (1952); Manson-Haferd (1953); Sherby-Dorn (1954); Monkman-Grant (1956); Omega (1995); Theta (1992); Kachanov-Rabotnov (1967-69); Wilshire (2006); Sinh (2013); etc.

Fatigue Rupture

- Palmgren-Miner (1924,1945); Robinson (1938); Lieberman (1962); Coffin-Manson (1953-54); Morrow-Halford (1965-66); Chaboche (1988); Scott-Emuakpor (2011); etc.

Creep-Fatigue Rupture

- Manson (1971), British R5; Chaboche (1980), ASME B&PV III, French RCC; etc.

Constitutive Laws

Creep Viscoplasticity (Zero Yield Surface)

- Primary: Andrade (1910); Bailey (1935); McVetty (1943); Garofalo (1965); etc.
- Secondary: Norton (1929); Soderberg (1936); McVetty (1943); Dorn (1955); Johnson-Henderson-Kahn (1963); Garofalo (1965); etc.
- Mixed: McVetty (1943); Graham and Walles (1955); Garofalo (1965); Kachanov-Rabotnov (1967-69); Theta (1984); RCC-MR (1985); Omega (1995); Liu-Murakami (1998); Dyson-McClean (1998); Sinh (2013); etc.

Cyclic Viscoplasticity (Yield Surface)

- Bodner (1975); Hart (1976); Chaboche (1977); Robinson (1978); Krempl (1980);etc.

Creep-Fatigue Viscoplasticity (Equilibrium Surface)

- Miller (1976); Walker (1981); Sinh (2013); etc.

There are Many More!…

The Team

Dr. Calvin M Stewart, Project PI

Dr. Jack F Chessa, Project Co-PI

Alumni

Mohammad
Shafinul Haque
**Tenure Track
Asst. Professor
at Angelo State
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Alumni

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**Metallurgy Test
Technician at
Element**

Current Members

Md Abir Hossain
Ph.D.

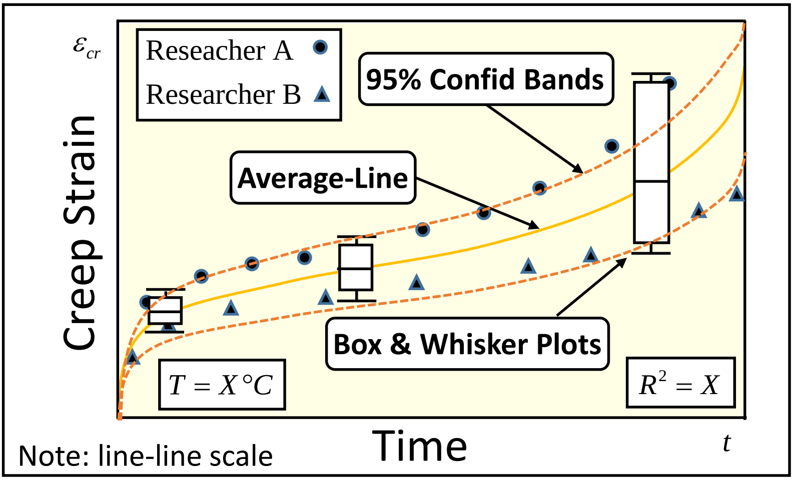
Jaime Cano
MS

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

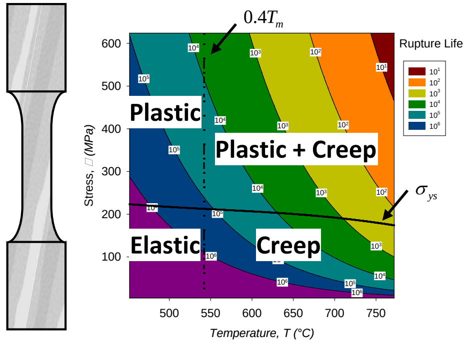
Global Optimization

MACHO

MAterial Constant Heuristic Optimization

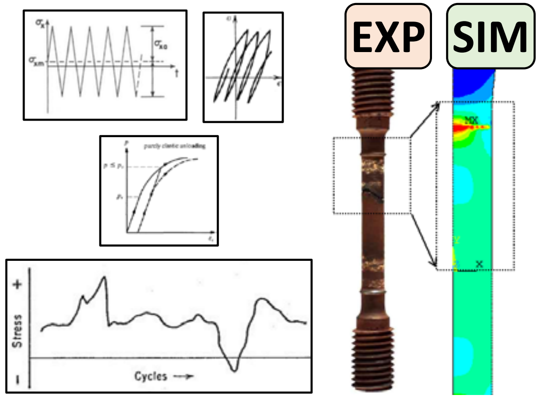
Model Fit to Datasets

Interpolation & Extrapolation



Standard Performance

Post-Audit Validation



Nonstandard Performance

Model Uncertainty

$NMSE, Z_{CRMS}$

Performance

A B C D F

Project Tasks

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

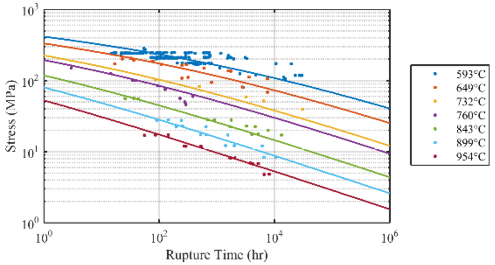
Creep Data Thus Far…

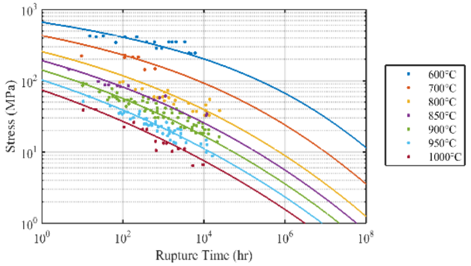
Alloys:
P91
316SS/N

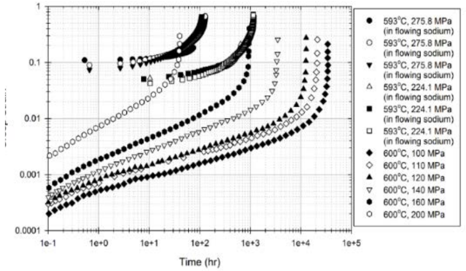
Planned:
304SS
IN617
IN625
IN718
…

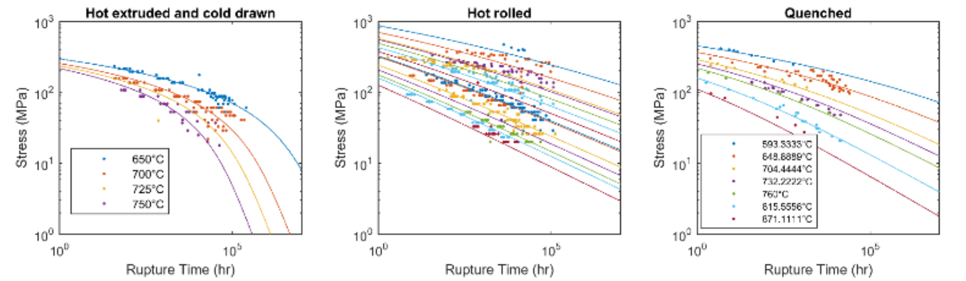
Source	Creep Deformation	Stress Relaxation	Min. Strain Rate	Time to Cr. Strain	Creep Rupture	Mono. Tensile	Cyclic Hysteresis	Stress Amp/Cycle	Cr.-Fatigue Tensile
ARL-79-33		9							16
ASM Atlas of Creep & Stress-Rupture	20								
ASM Atlas of Fatigue									
ASM Atlas off Stress-Corrosion Fatigue					14			42	14
ASM Atlas of Stress-Strain						106			
ASTM DS-60									
ASTM DS5-S1			144		295				
ASTM STP 124			43	22	85				
ASTM STP 522			135	90	160			24	
Booker and Sikka, 1976				183					
Choudary, 2009			56				13	4	13
Fournier (1), 2008								29	
Fournier (2), 2008							2	12	18
Fournier (3), 2008		13						19	161
Nagesha, 2002									
NIMS Database		210	245	764	1184	207			
ORNL TM-10504	9		38	46	12				
ORNL-101053									
ORNL/TM-6608									
ORNL-5237	6		52		55				
Rau, 2002							30	18	
Rowe, 1963	69		96	78	96				
Shankar, 2006								51	6
Takahasi, 2008									51
Yan, 2015									399
Kimura, 2009			33						

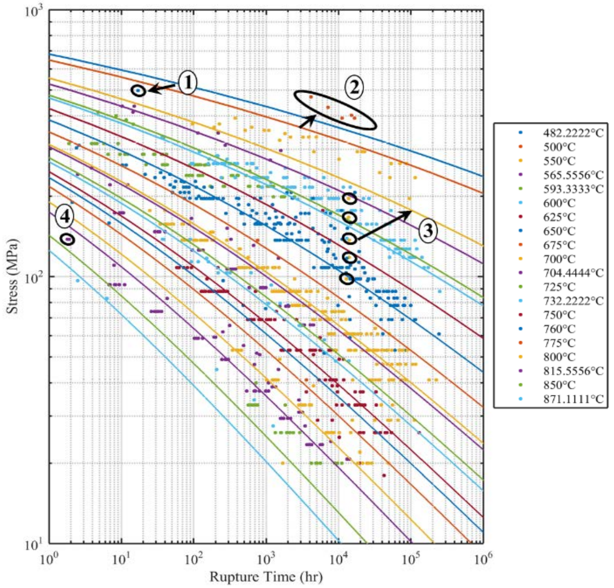
Creep Data Work Thus Far…

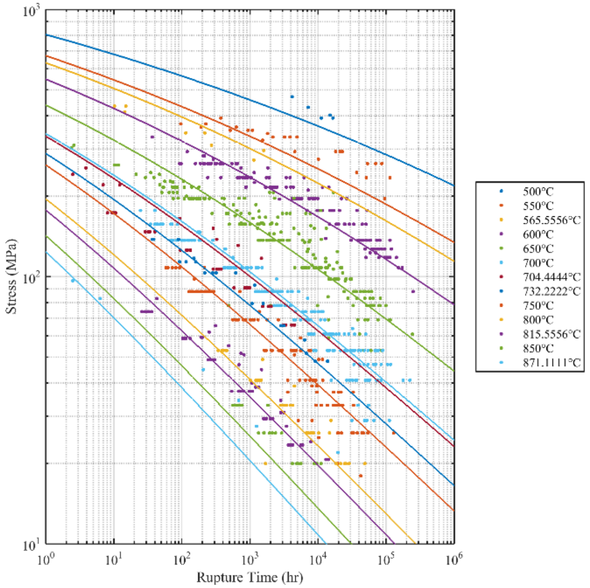


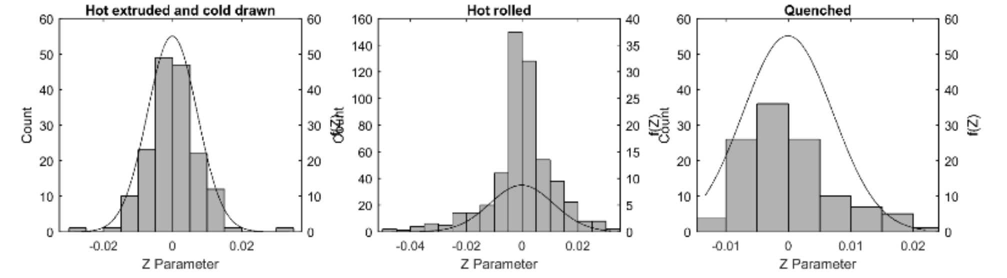


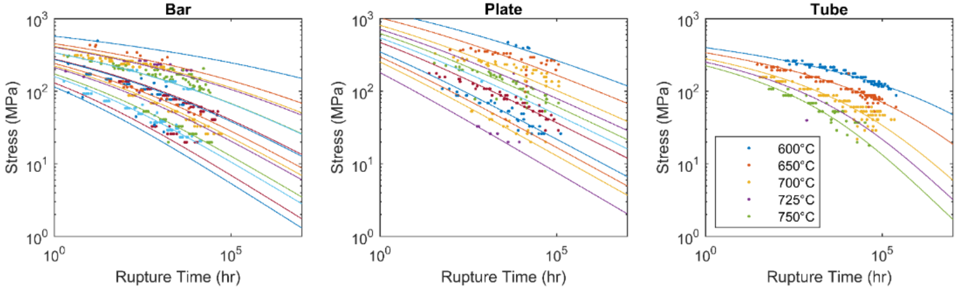


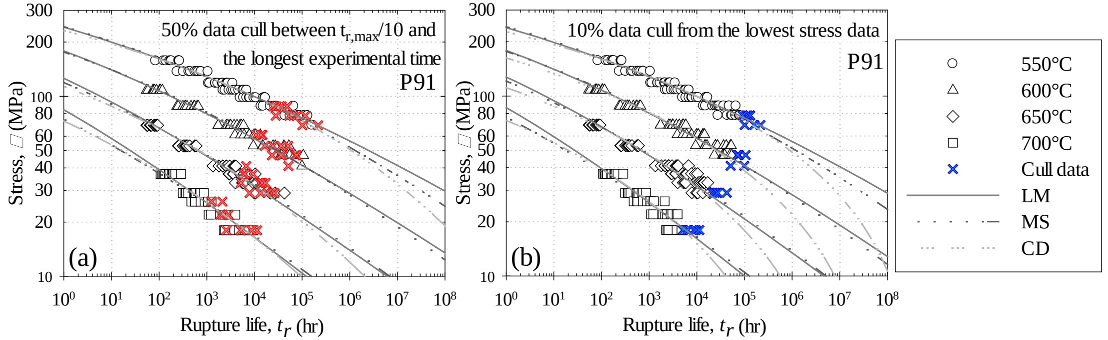


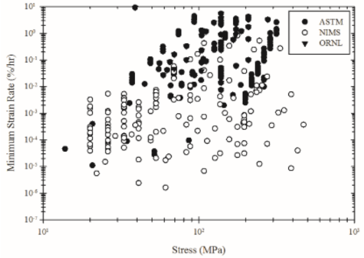


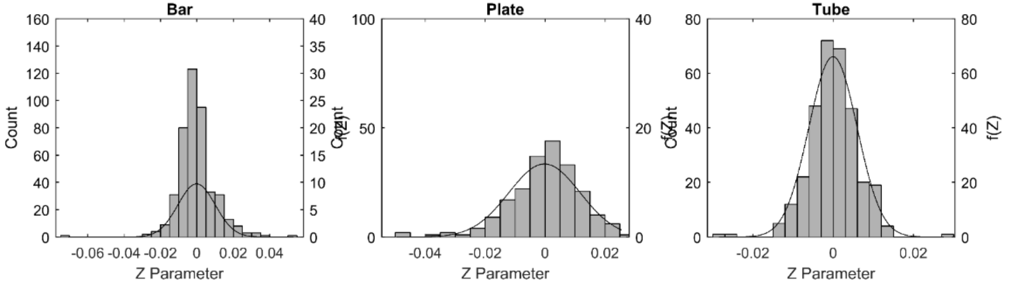












List of Publication

- Journal Articles
  - Hossain, M.A., and Stewart, C.M., 2019, “Reliability Prediction of Sine-Hyperbolic Creep-Damage Model using Monte Carlo Simulation Method,” Journal TBD, (in preparation).
  - Cano, J., and Stewart, C.M., 2019, “Application of the Wilshire Stress-Rupture and Minimum-Creep-Strain-Rate Prediction Models for Alloy P91 in Tube, Plate And Pipe Form,” Journal TBD, (in preparation).
  - Vega, R., and Stewart, C.M., 2019, “Development and Application Of Minimum Creep Strain Rate Metamodeling,” Journal TBD, (in preparation).
  - Haque, M.S., and Stewart C.M., 2019, “Metamodeling Time-Temperature Parameters for Creep,” *Materials at High Temperatures* (under review). MHT-S-18-00109
  - Haque, M.S, and Stewart, C. M., 2019, “Comparative Analysis of the Sin-Hyperbolic and Kachanov–Rabotnov Creep-Damage Models,” *International Journal of Pressure Vessels and Piping*, (in-press), https://doi.org/10.1016/j.ijpvp.2019.02.001 [PDF]
  - Haque, M.S, and Stewart, C. M., 2019, “The Disparate Data Problem: The Calibration of Creep Laws Across Test Type and Stress, Temperature, and Time Scales,” *Theoretical and Applied Fracture Mechanics*, **100**, https://doi.org/10.1016/j.tafmec.2019.01.018 [PDF]
  - Haque, M. S., and Stewart, C. M., 2017, “The Stress-Sensitivity, Mesh-Dependence, and Convergence of Continuum Damage Mechanics Models for Creep,” *ASME Journal of Pressure Vessel Technology*, **139**(4). doi:10.1115/1.4036142

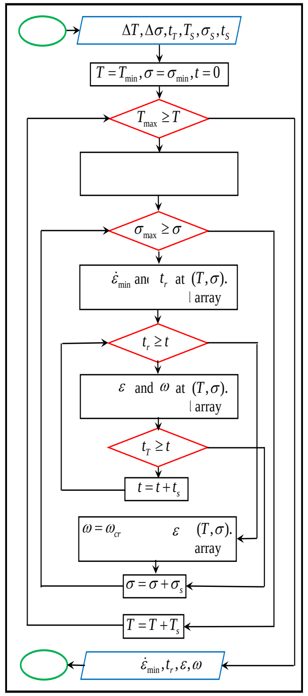
List of Publication(cont…)

- Conference Papers
  - Hossain, M.A., and Stewart, C.M., 2019, “Reliability Prediction of Sine-Hyperbolic Creep-Damage Model using Monte Carlo Simulation Method,” ASME PVP 2019, San Antonio, Texas, July 14 – 19, 2019. (accepted).
  - Cano, J., and Stewart, C.M., 2019, “Application of the Wilshire Stress-Rupture and Minimum-Creep-Strain-Rate Prediction Models for Alloy P91 in Tube, Plate And Pipe Form,” ASME TurboExpo 2019, Phoenix, Arizona, June 17-21, 2019.
  - Perez, J., and Stewart, C.M., 2019, “Asssessment of the Theta Projection Model for Interpolating Creep Deformation,” ASME TurboExpo 2019, Phoenix, Arizona, June 17-21, 2019.
  - Vega, R., and Stewart, C.M., 2019, “Development and Application Of Minimum Creep Strain Rate Metamodeling,” ASME TurboExpo 2019, Phoenix, Arizona, June 17-21, 2019.
  - Haque, M. S., and Stewart, C. M., 2017, “Selection of Representative Stress Function under Multiaxial Stress State Condition for Creep,” *ASME PVP 2017*, PVP2017-65296, Waikoloa, HI, July 16-20, 2017.
  - Haque, M. S., Ramirez, C., and Stewart, C. M., 2017, “A Novel Metamodeling Approach for Time-Temperature Parameter Models,” *ASME PVP 2017*, PVP2017-65297, Waikoloa, HI, July 16-20, 2017.
  - Ramirez, C., Haque, M. S., and C. M. Stewart, 2017, “Guidelines to the Assessment of Creep Rupture Reliability for 316SS using the Larson-Miller Time-Temperature Parameter Model,” ASME PVP 2017, PVP2017-65816, Waikoloa, HI, July 16-20, 2017. https://doi.org/10.1115/PVP2017-65816

List of Publication(cont…)

- Short Papers
    - Vega, R., and Stewart, C.M., 2019, “Metamodeling of Minimum Creep Strain Rate Models with Temperature Dependence,” SETS 2019, EL Paso, TX, March 26-27, 2019.
    - Perez, J., and Stewart, C.M., 2019, “An Alternative Method for Interpolating and Extrapolating Strain Predictions Using the Theta Projection Model,” SETS 2019, EL Paso, TX, March 26-27, 2019.
    - Hossain, M. A., and Stewart C.M., 2019, “Probabilistic Evaluation of 304 Stainless Steel using Sine Hyperbolic Creep-Damage Model,” SETS 2019, EL Paso, TX, March 26-27, 2019.
    - Cano, J., and Stewart, C.M., 2019, “Modified Wilshire Model for Long-Term Creep Deformation” SETS 2019, El Paso, TX, March 26-27, 2019.
    - Vega, R., and Perez, J., and Stewart, C. M., 2018, “Identification of Creep Strain Constants and Accurate Model Fits using Numerical Optimization,” SETS 2018, El Paso, TX, April 14th, 2018.
    - Haynes, A., Stewart, C. M., 2017, “The Numerical Analysis of Equivalent Stress Functions for Multiaxial Creep Deformation, Damage, and Rupture,” SETS 2017, El Paso, TX, April 1st, 2017.
    - Ramirez, C., Haque, M. S., and Stewart, C. M., 2017, “Guidelines to the Assessment of Creep Rupture Uncertainty for 316SS using the Larson-Miller Time-Temperature Parameter Model,” SETS 2017, El Paso, TX, April 1st, 2017.

Previous Works



Temperature-range = $\Delta T = T_{max} - T_{min}$

$\Delta\sigma = \sigma_{max} - \sigma_{min}$

t_T

$= t_r = f(T,\sigma)$

T_s, σ_s, t_s

T, σ, t

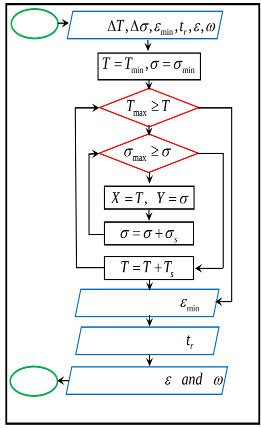
$\dot{\varepsilon}_{min} = f(T,\sigma)$

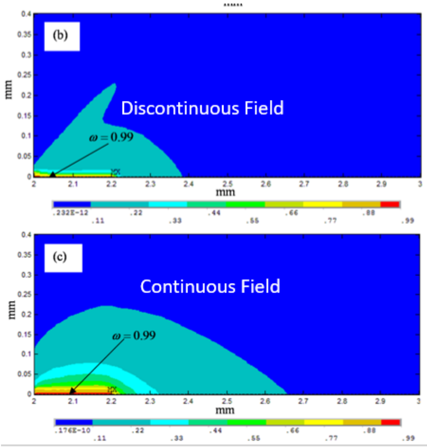
$: f(T)$

$\omega,$ ω_{cr}

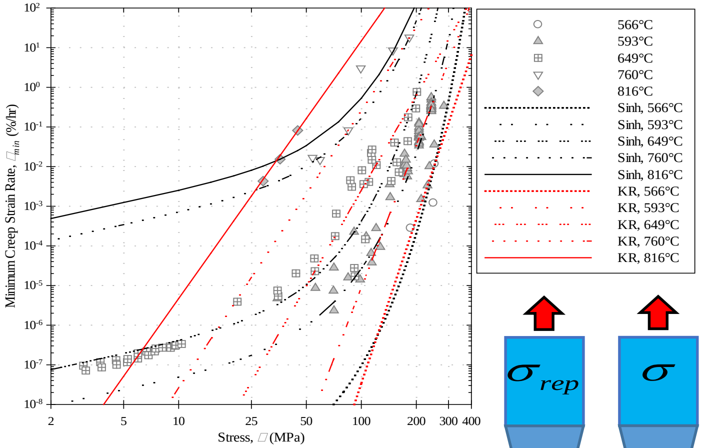
ε

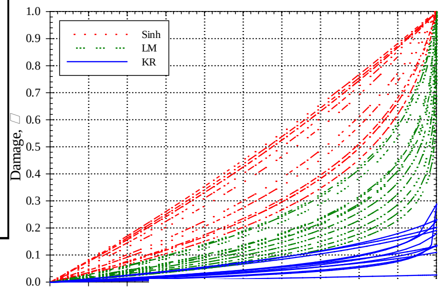
$X, Y =$

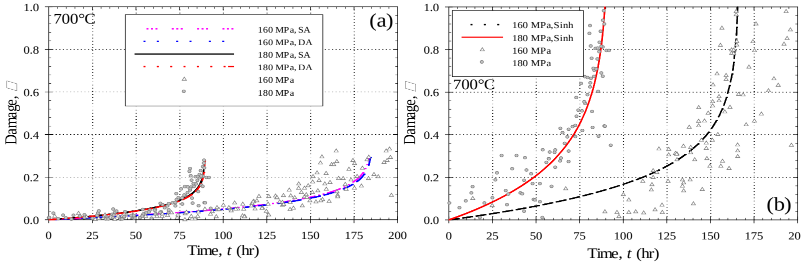


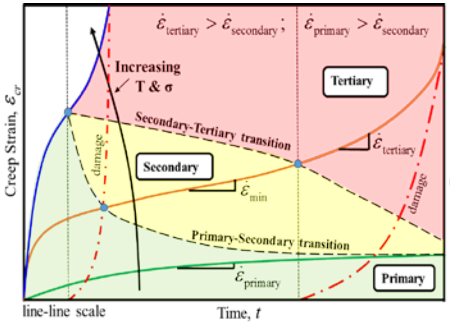


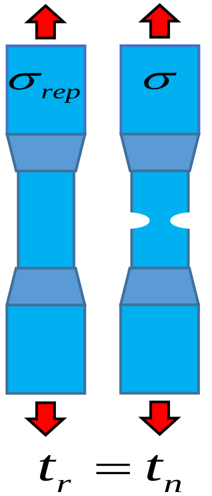
Model	Year	Parametric equation	Iso-stress equation	Material constants	Characteristics	Metamodel condition	Ref.
			$P_{unified} = \frac{\log(t_r) - \alpha_0 - \alpha_1 T^r}{(T^r - \alpha_2^r)^q}$				
Larson-Miller	1952	$P_{LMP} = T(\log(t_r) + t_a)$	$\log(t_r) = \frac{P_{LMP}}{T} - t_a$	$P_{LMP}(\sigma)$, t_a	Cy, L, NP, Sp	$\alpha_1 = \alpha_2 = 0$ $r = -1, q = 1$	11
Manson-Haferd	1953	$P_{MH} = \frac{\log(t_r) - \log(t_a)}{T - T_a}$	$\log(t_r) = P_{MH}(T - T_a) + \log(t_a)$	$P_{MH}(\sigma)$, T_a, t_a	Cxy, L, NP, Sn	$\alpha_1 = 0$ $r = q = 1$	3
Manson-Brown	1953	$P_{MB} = \frac{\log(t_r) - \log(t_a)}{(T - T_a)^n}$	$\log(t_r) = P_{MB}(T - T_a)^n + \log(t_a)$	$P_{MB}(\sigma)$, T_a, t_a, n	Cxy, NL, NP, Snv	$\alpha_1 = 0, r = 1$, $q = n$	12
Orr-Sherby-Dorn	1954	$P_{OSD} = \log(t_r) - Q / RT$	$\log(t_r) = Q / RT + P_{OSD}$	$P_{OSD}(\sigma)$, Q, R	NC, L, P, Sp=constant	$\alpha_0 = 0, r = -1$, $q = 0$	13
Manson-Succop	1959	$P_{MS} = \log(t_r) - BT$	$\log(t_r) = BT + P_{MS}$	$P_{MS}(\sigma)$, B	NC, L, P, Sn=constant	$\alpha_0 = \alpha_2 = 0$, $r = 1, q = 0$	14
Graham-Walles	1955	$P_{GW} = \frac{\log(t_r)}{(T - T_a)^n}$	$\log(t_r) = P_{GW}(T - T_a)^n$	$P_{GW}(\sigma)$, T_a, n	Cx, NL, NP, Snv	$\alpha_0 = \alpha_1 = 0$, $r = 1, q = n$	15
Chitty-Duval	1963	$P_{CD} = mT - \log(t_r)$	$\log(t_r) = mT - P_{CD}$	P_{CD}, $m = a\sigma^b$	NC, NP, L, Sn	$\alpha_0 = \alpha_2 = 0$, $r = 1, q = 0$	16
Goldhoff-Sherby	1968	$P_{GS} = \frac{\log(t_r) - \log(t_a)}{1/T - 1/T_a}$	$\log(t_r) = P_{GS}(1/T - 1/T_a) + \log(t_a)$	$P_{GS}(\sigma)$, T_a, t_a	Cxy, L, NP, Sp	$\alpha_1 = 0, r = -1$, $q = 1$	17
Modified Manson-Haferd	--	$P_{MMH} = \frac{\log(t_r) - \log(t_a)}{T}$	$\log(t_r) = P_{MMH} T + \log(t_a)$	$P_{MMH}(\sigma)$, t_a	Cy, L, NP, Sn	$\alpha_1 = \alpha_2 = 0$, $r = 1, q = 1$	--
Modified Graham-Walles	--	$P_{MGW} = \frac{\log(t_r)}{(1/T - 1/T_a)^n}$	$\log(t_r) = P_{MGW}(1/T - 1/T_a)^n$	$P_{MGW}(\sigma)$, T_a, n	Cx, NL, NP, Spv	$\alpha_0 = \alpha_1 = 0$ $r = -1, q = n$	--
Modified Chitty-Duval	--	$P_{CD} = \frac{m}{T} - \log(t_r)$	$\log(t_r) = m / T - P_{CD}$	P_{CD}, $m = a\sigma^b$	NC, NP, L, Sp	$r = -1, q = 0$, $\alpha_0 = \alpha_2 = 0$	--
Modified-Goldhoff-Sherby	--	$P_{GS} = \frac{\log(t_r) - \log(t_a)}{(1/T - 1/T_a)^n}$	$\log(t_r) = P_{MGS}(1/T - 1/T_a)^n + \log(t_a)$	$P_{MGS}(\sigma)$, T_a, t_a	Cxy,NL, NP, Sp	$r = -1, q = n$, $\alpha_1 = 0$	--

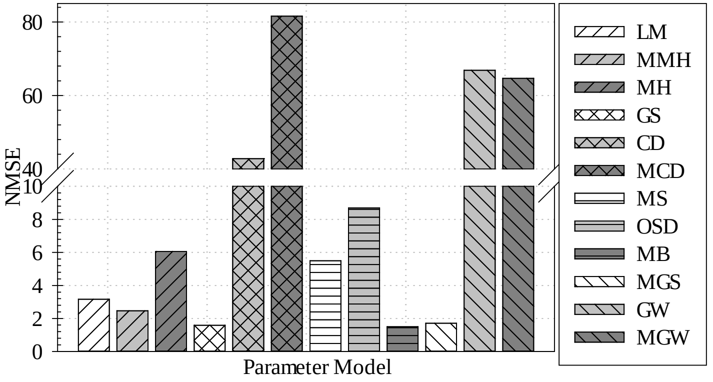


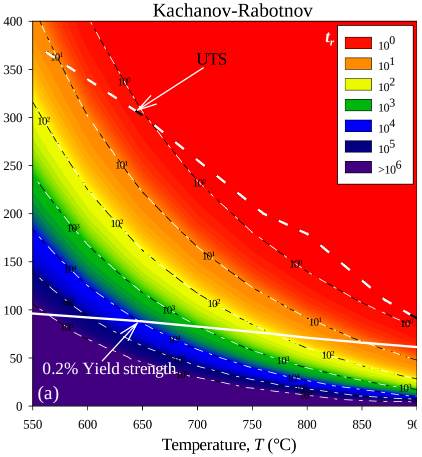


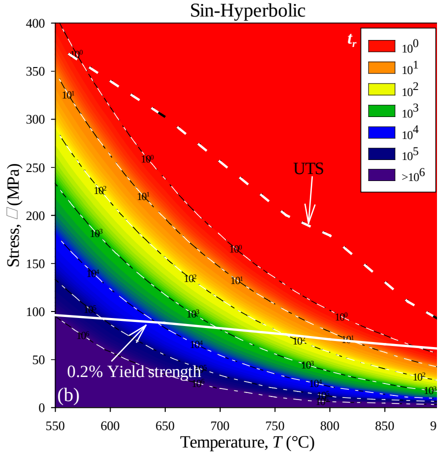


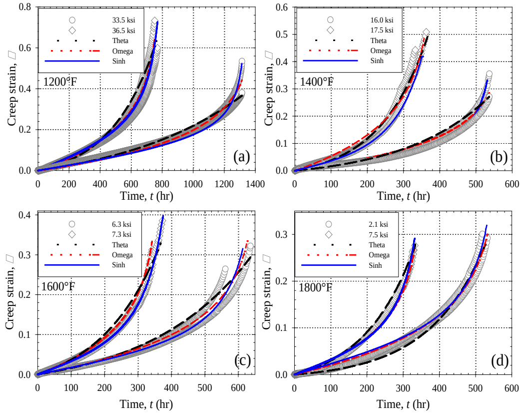


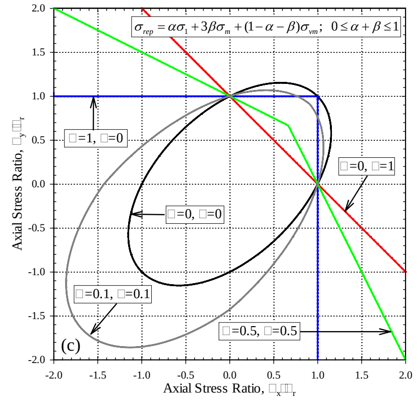












Ongoing Work

1. A modified Wilshire Model for Creep Deformation, Damage, and Rupture Prediction
2. An Analytical Calibration for a Modified Theta-Projection Model
3. Metamodeling Minimum Creep Strain Rate Laws
4. A Probabilistic Approach to Creep Deformation, Damage, and Rupture Prediction

A Modified Wilshire Model

Jaime Cano

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

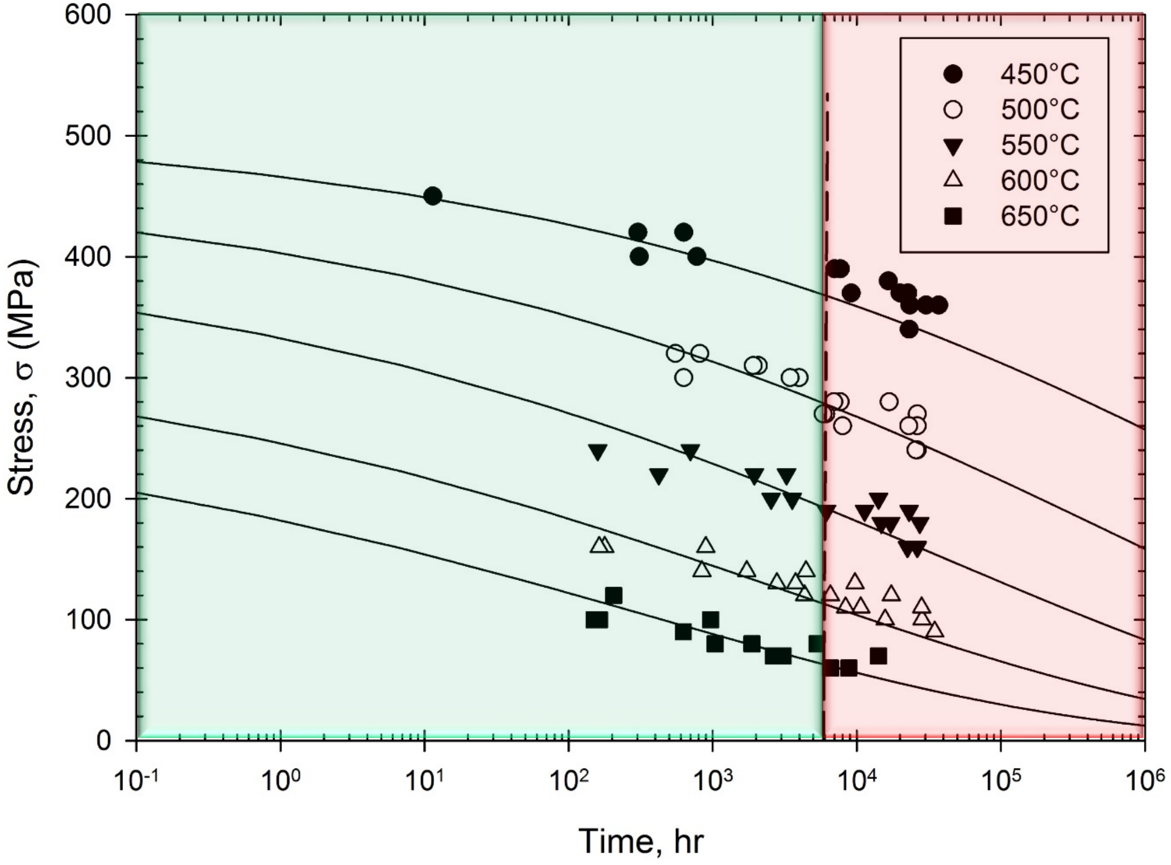
- Cano, J., and Stewart, C.M., 2019, “Application of the Wilshire Stress-Rupture and Minimum-Creep-Strain-Rate Prediction Models for Alloy P91 in Tube, Plate And Pipe Form,” ASME TurboExpo 2019, Phoenix, Arizona, June 17-21, 2019.
- Cano, J., and Stewart, C.M., 2019, “Modified Wilshire Model for Long-Term Creep Deformation” SETS 2019, El Paso, TX, March 26-27, 2019.

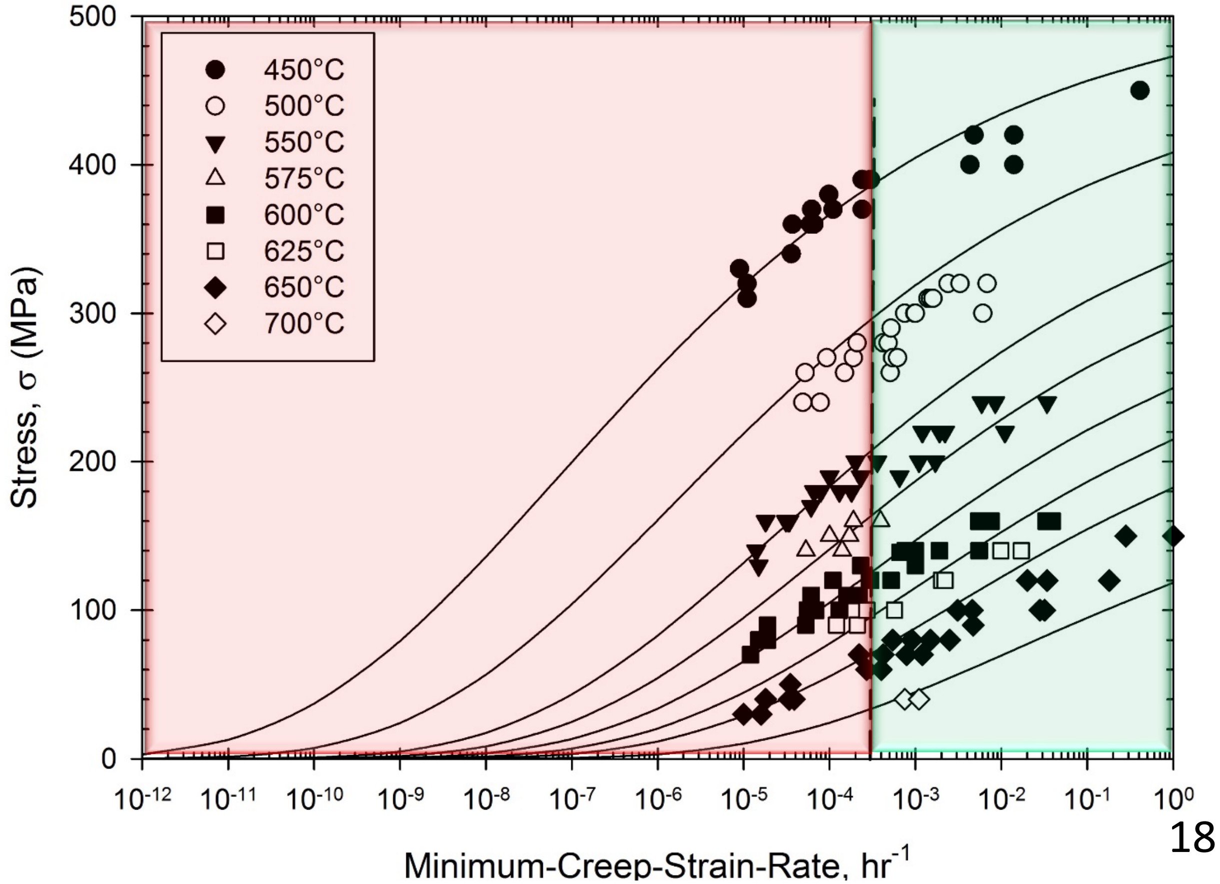
Wilshire Model

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

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

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





Continuum Damage Mechanics (CDM) Framework

Insertion of Wilshire Model into Sinh CDM Model

Sine-Hyperbolic (Sinh) Framework

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

Sinh deformation model

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

Damage Model

Wilshire Model Framework

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

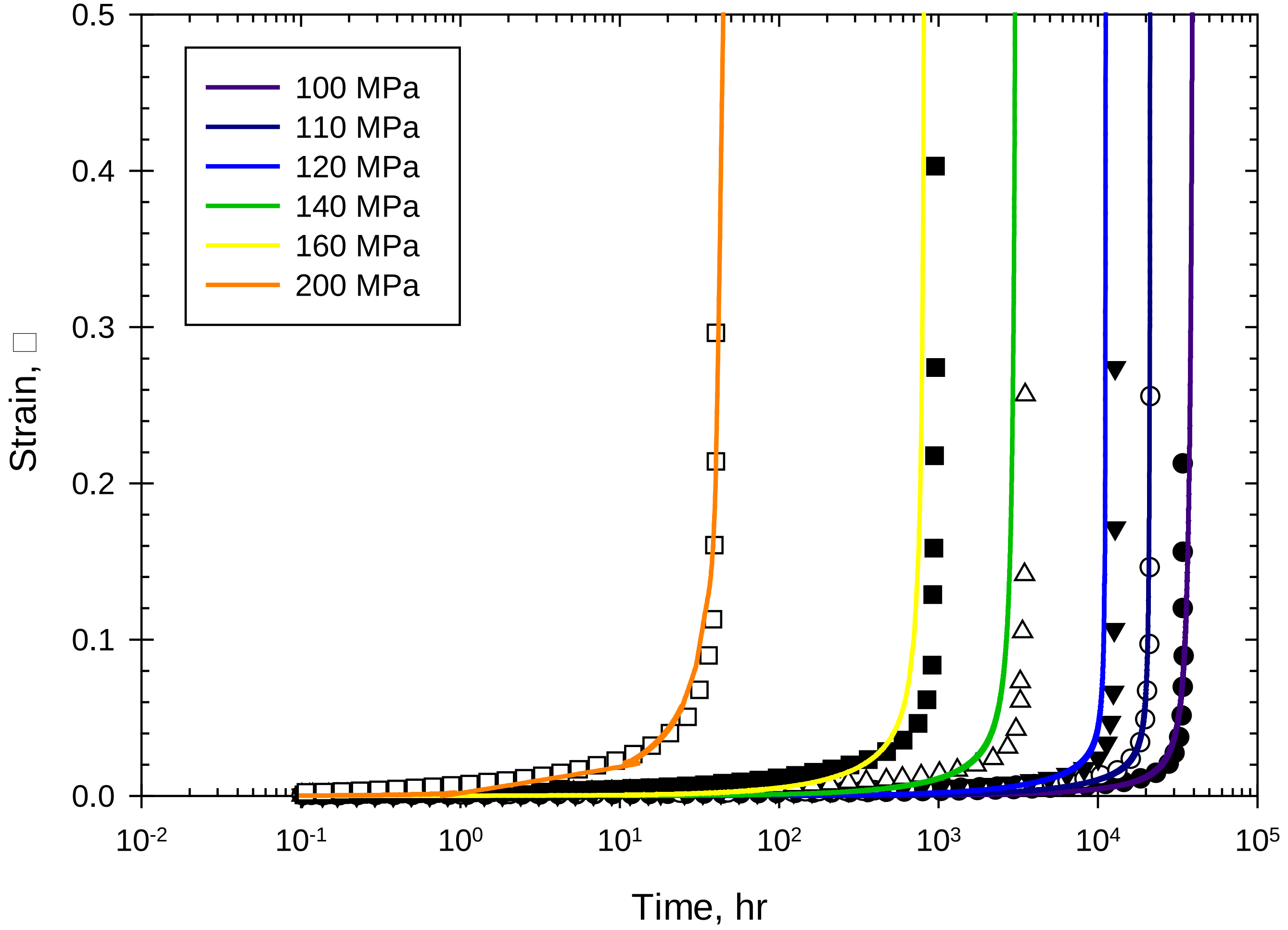
Minimum-creep-strain-rate

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

Time of Rupture

Modified Wilshire Model

P91 Data @ 600 °C



- 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.

Analytical Calibration Approach to Theta-Projection

Jimmy J Perez

Biography

- BS in Mechanical Engineering; The University of Texas at El Paso (2013-2017).
- 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

- Perez, J., and Stewart, C.M., 2019, "Asssessment of the Theta Projection Model for Interpolating Creep Deformation," ASME TurboExpo 2019, Phoenix, Arizona, June 17-21, 2019.
- Perez, J., and Stewart, C.M., 2019, "An Alternative Method for Interpolating and Extrapolating Strain Predictions Using the Theta Projection Model," SETS 2019, EL Paso, TX, March 26-27, 2019.

Analytical Calibration Approach to Theta-Projection

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.

Theta-Projection model

$$\varepsilon = \theta_1(1 - \exp(-\theta_2 t)) + \theta_3(\exp(\theta_4 t) - 1)$$

Primary and tertiary equation are separated

Primary equation

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

Tertiary equation

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

The accumulated primary strain is equated to θ_1 and is used to back-solve for θ_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 θ_3.

Primary strain accumulation

$$\theta_1 = \varepsilon_{pr,acc}$$

Back-solved exponential decay constant

$$\theta_2 = -\frac{1}{t_{pr,sub-acc}} \ln(1 - \frac{\varepsilon_{pr,sub-acc}}{\theta_1})$$

Back-solved tertiary scalar

$$\theta_3 = \frac{\varepsilon_{95\%} - \theta_1}{\exp(\theta_4 t_{95\%}) - 1}$$

Tertiary acceleration

$$\theta_4 = \frac{\ddot{\varepsilon}_{95\%}}{\dot{\varepsilon}_{95\%}}$$

Modified Interpolation/Extrapolation Functions

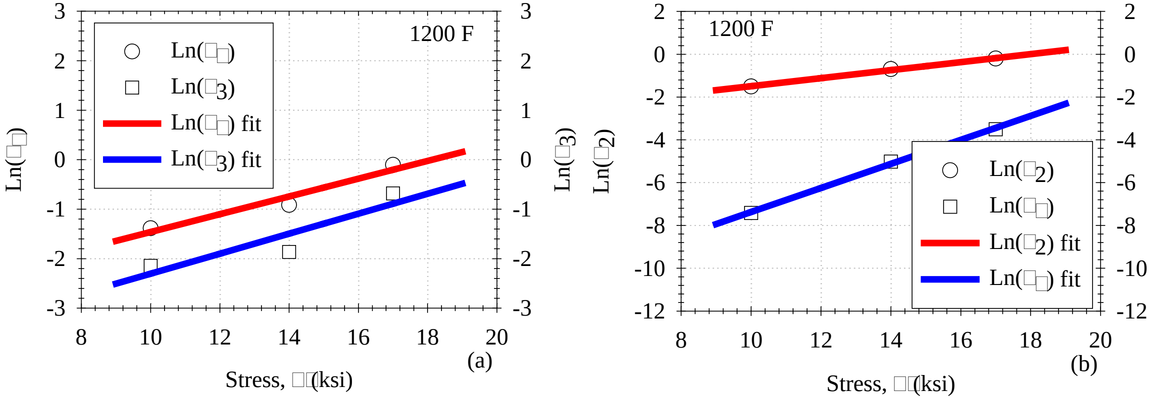
The original interpolation/extrapolation function used with the **Thera-projection model** does not consistently provide good predictions with **limited data**. A much more consistent trend with rupture time is proposed for prediction. The error between the new function and the calibrated theta constants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

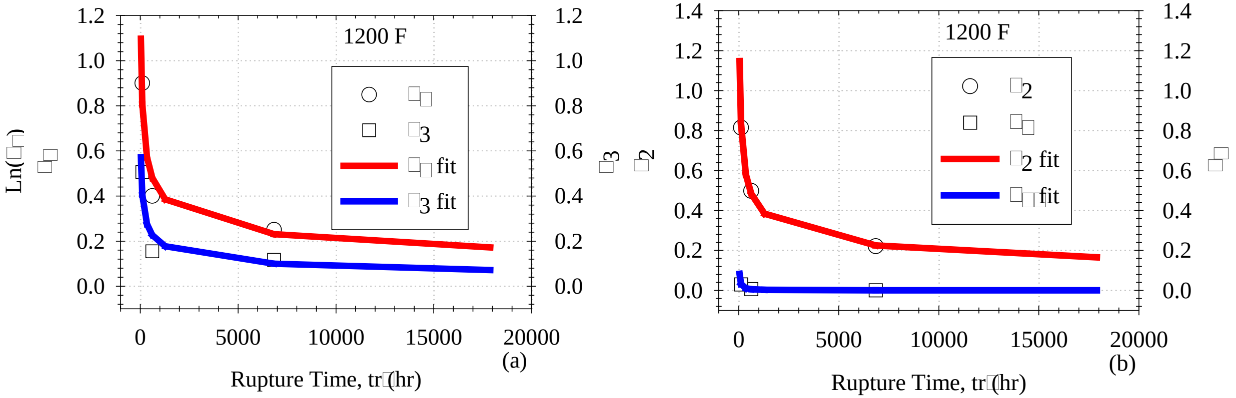
Original interpolation/extrapolation function

$$\theta_i = \exp(a_i + b_i\sigma + c_iT + d_i\sigma T)$$

Alternative interpolation/extrapolation function

$$\theta_i = A_i(t_r)^{-B_i}$$





	θ_1 NMSE	θ_2 NMSE	θ_3 NMSE	θ_4 NMSE
Alternative function	0.0190	4.9527e-4	0.0921	2.2936e-3
Original function	0.0167	9.2036e-4	0.0855	5.3149e-3
% Improvement	12	85	7	131

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

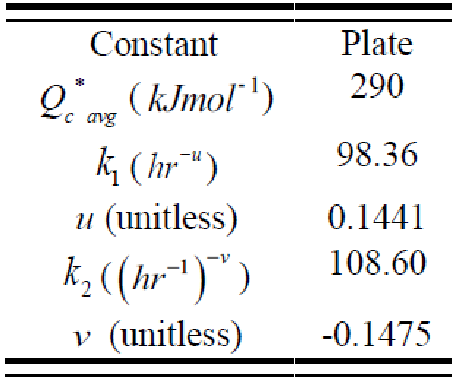
$$\frac{\sigma}{\sigma_{TS}} = \exp(-k_1\left[t_r\exp(-\frac{Q_c^*}{RT})\right]^u)$$

→

Rearranged to relate experimental stress and temperature to rupture time

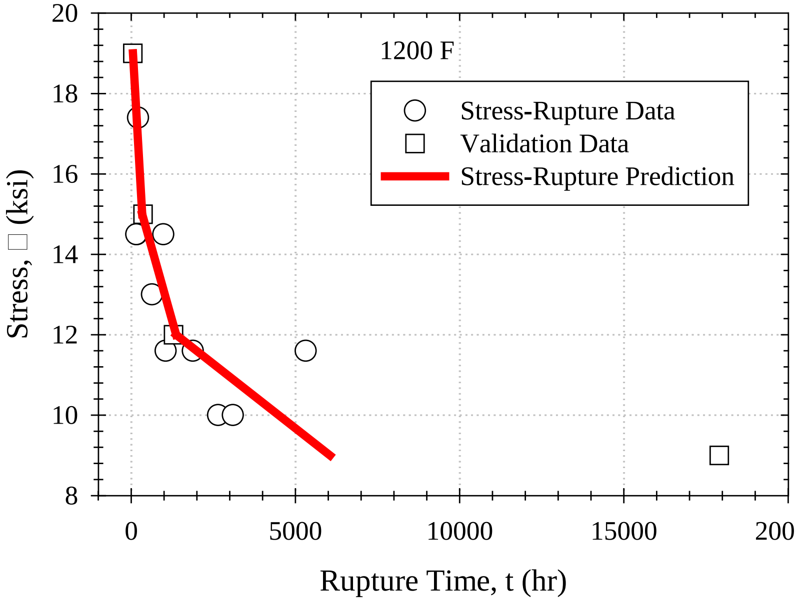
$$t_r = \frac{1}{\exp(-\frac{Q_c^*}{RT})}\left(\frac{\ln(\frac{\sigma}{\sigma_{TS}})}{-k_1}\right)^{1/u}$$

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



Constant	Plate
$Q^*_{c\ avg}$ $(kJmol^{-1})$	290
k_1 (hr^{-u})	98.36
u (unitless)	0.1441
k_2 $((hr^{-1})^{-v})$	108.60
v (unitless)	-0.1475

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



Metamodeling Minimum-Creep-Strain-Rate Laws

Ricardo Vega

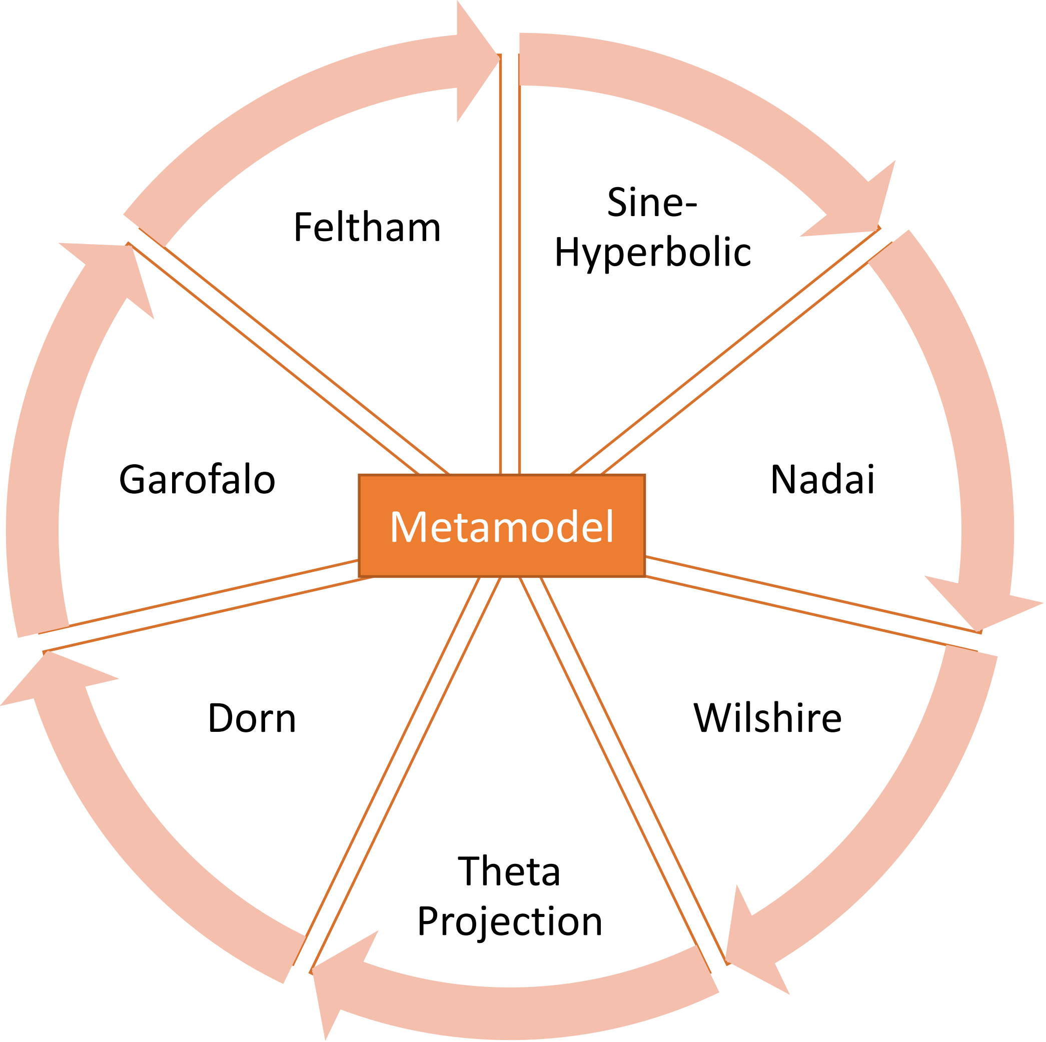
Biography

- 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

- Vega, R., and Stewart, C.M., 2019, “Development and Application Of Minimum Creep Strain Rate Metamodeling,” ASME TurboExpo 2019, Phoenix, Arizona, June 17-21, 2019.
- Vega, R., and Stewart, C.M., 2019, “Metamodeling of Minimum Creep Strain Rate Models with Temperature Dependence,” SETS 2019, EL Paso, TX, March 26-27, 2019.
- Vega, R., and Perez, J., and Stewart, C. M., 2018, “Identification of Creep Strain Constants and Accurate Model Fits using Numerical Optimization,” SETS 2018, El Paso, TX, April 14th, 2018.

Metamodeling Minimum-Creep-Strain-Rate Laws



- **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.

Minimum-Creep-Strain-Rate Models

Model	Equation
Norton 1929	$\dot{\varepsilon}_{\min} = A\left(\frac{\sigma}{\sigma_0}\right)^n * \exp\left(\frac{-Q_c^*}{RT}\right)$
Simplified Norton 1929	$\dot{\varepsilon}_{\min} = A\sigma^n * \exp\left(\frac{-Q_c^*}{RT}\right)$
Nadai 1931	$\dot{\varepsilon}_{\min} = A\exp(\frac{1}{\sigma_0} + c\sigma) * \exp\left(\frac{-Q_c^*}{RT}\right)$
Soderberg 1936	$\dot{\varepsilon}_{\min} = A\left\{\exp\left(\frac{\sigma}{\sigma_0}\right) - 1\right\} * \exp\left(\frac{-Q_c^*}{RT}\right)$
McVetty 1943	$\dot{\varepsilon}_{\min} = A\sinh\left(\frac{\sigma}{\sigma_0}\right) * \exp\left(\frac{-Q_c^*}{RT}\right)$
Dorn 1955	$\dot{\varepsilon}_{\min} = A\exp\left(\frac{\sigma}{\sigma_0}\right) * \exp\left(\frac{-Q_c^*}{RT}\right)$
Johnson-Henderson-Kahn 1936	$\dot{\varepsilon}_{\min} = [A_1\left(\frac{\sigma}{\sigma_0}\right)^{n_1} + A_2\left(\frac{\sigma}{\sigma_0}\right)^{n_2}] * \exp\left(\frac{-Q_c^*}{RT}\right)$
Garofalo 1965	$\dot{\varepsilon}_{\min} = A\left\{\sinh\left(\frac{\sigma}{\sigma_0}\right)\right\}^n * \exp\left(\frac{-Q_c^*}{RT}\right)$
Wilshire 2007	$\dot{\varepsilon}_{\min} = \left[-\ln(\frac{\sigma}{\sigma_{TS}}) / k_2\right]^{\frac{1}{v}} * \exp\left(\frac{-Q_c^*}{RT}\right)$

Proposed MCR Metamodel

- Metamodel (Constrained)

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

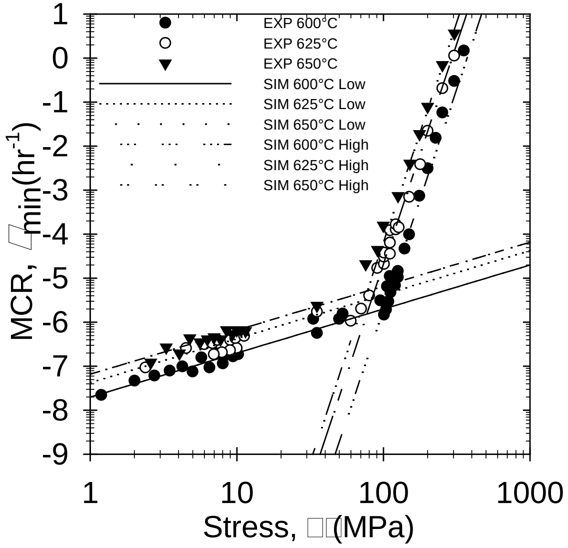
- Metamodel (Pseudo-Constrained)

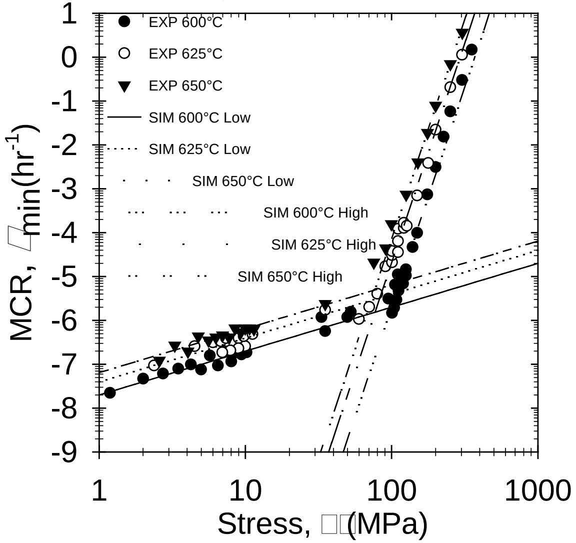
$$\dot{\varepsilon}_{\min} = H(x_1)A_1\left(\frac{\sigma}{\sigma_o}\right)^{n_1} + H(x_2)A_2\left(\frac{\sigma}{\sigma_o}\right)^{n_2} + H(x_3)A_3 \sinh\left(\frac{\sigma}{\sigma_o}\right)^{n_3} + H(x_4)A_4 \exp\left\{\left(\frac{\sigma}{\sigma_o}\right) - H(x_5)\alpha_o\right\}$$

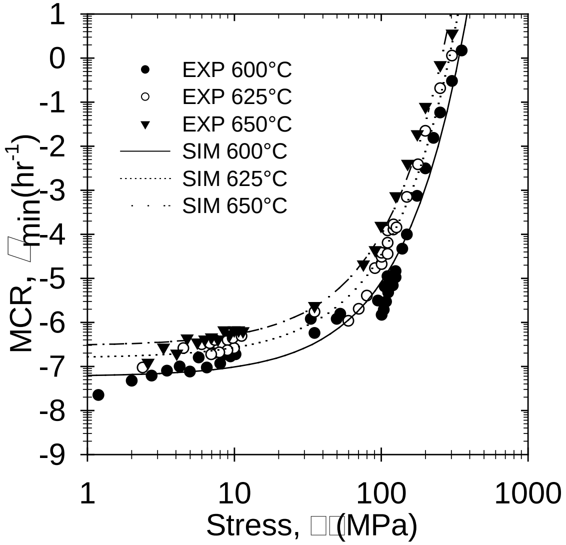
- Temperature Dependent Metamodel (Constrained)

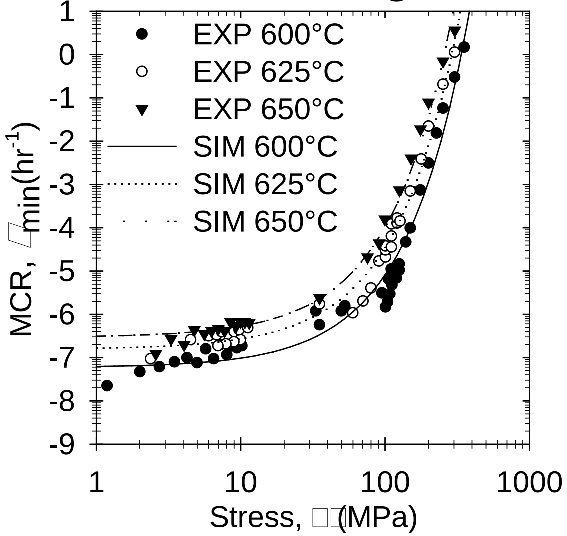
$$\dot{\varepsilon}_{\min} = \left[A_1\left(\frac{\sigma}{\sigma_o}\right)^{n_1} + A_2\left(\frac{\sigma}{\sigma_o}\right)^{n_2} + A_3 \sinh\left(\frac{\sigma}{\sigma_o}\right)^{n_3} + A_4 \exp\left(\frac{a_1}{\sigma_o} + c\sigma - a_2\right) + \left\{\frac{a_3 \ln\left(\frac{\sigma}{\sigma_o}\right)}{k_2}\right\}^{\frac{1}{v}}\right] \times \exp\left(-\frac{Q}{RT}\right)$$

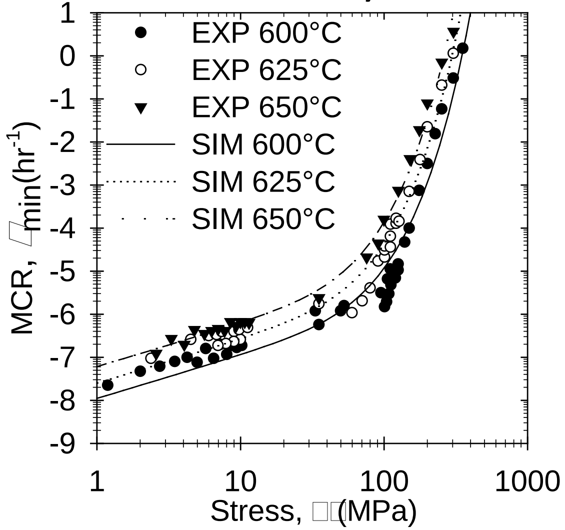
MCR Prediction for Different Models

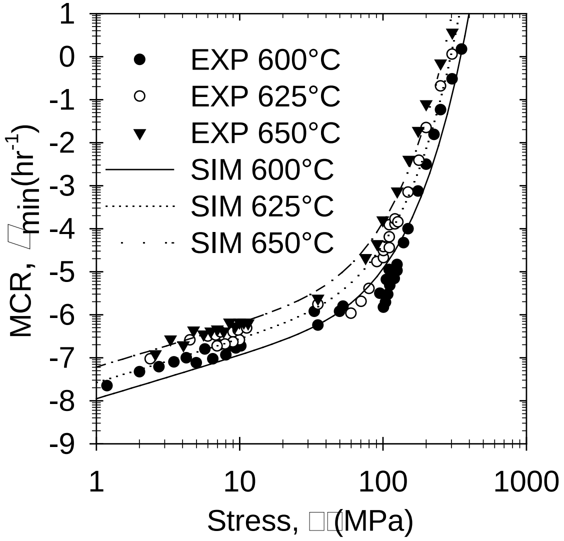

Norton


Simplified Norton


Dorn

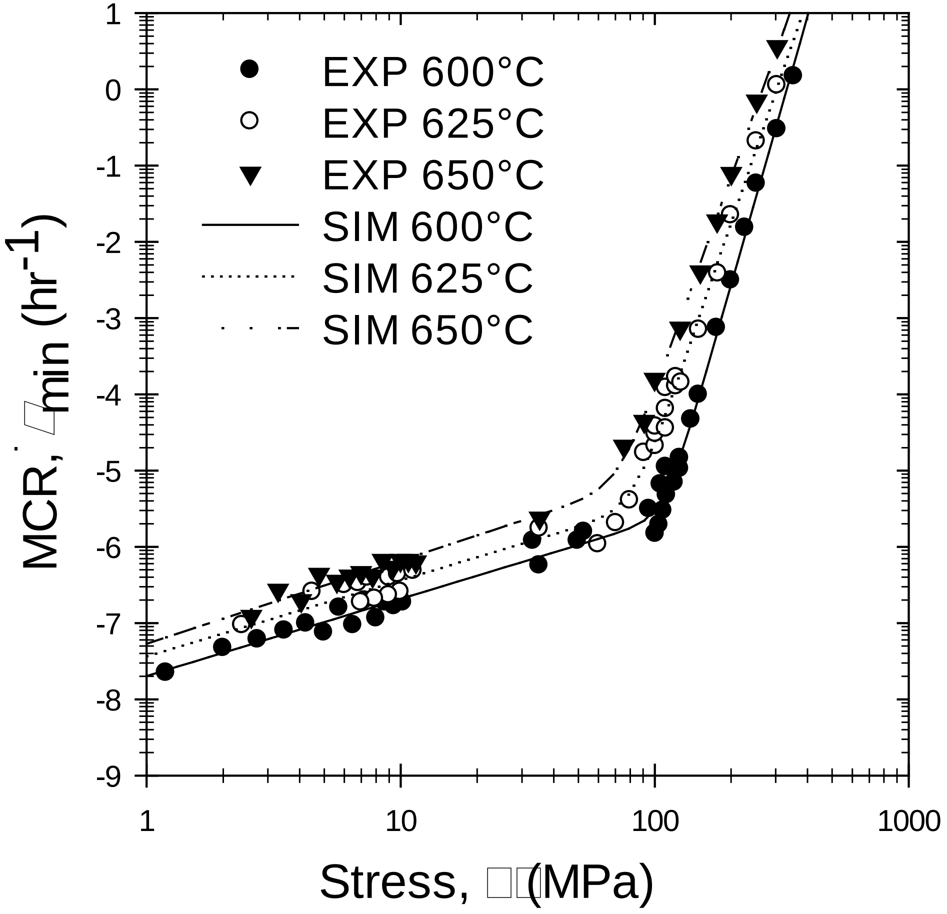

Soderberg


McVetty


Garofalo

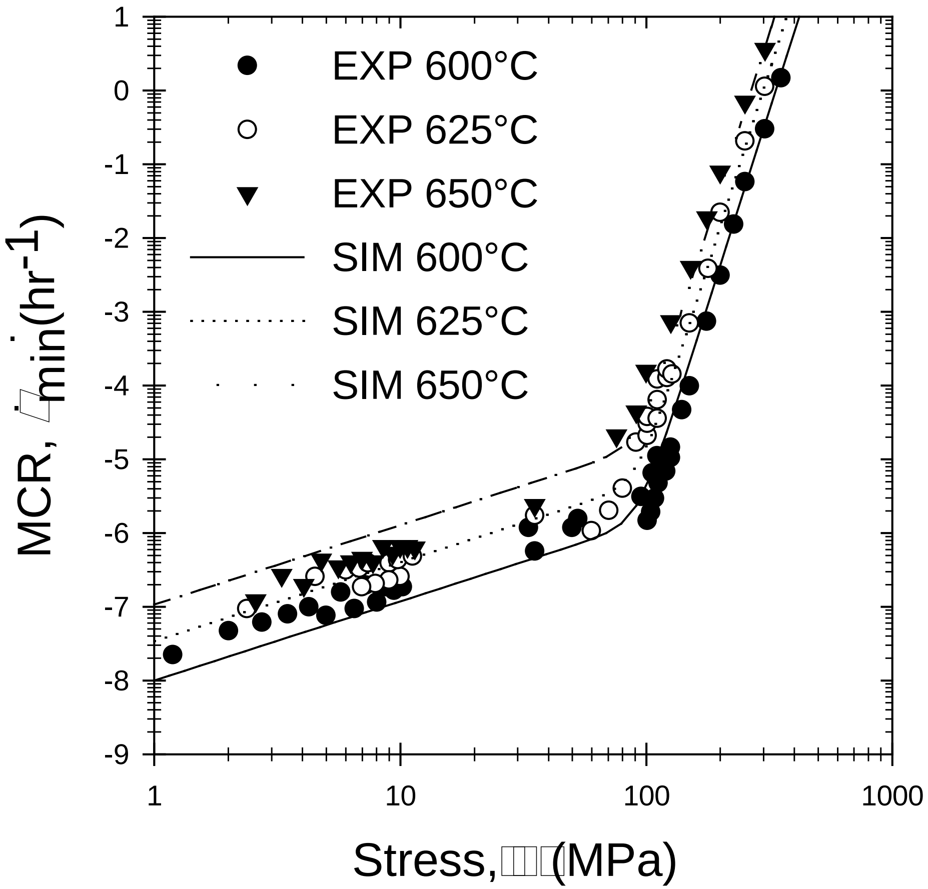
Generated Predictions

JHK Model, Pseudo-Constrained



Pseudo-Constrained	
Isotherm (°C)	NMSE
600	3.1575
625	0.1055
650	0.0833
Temp-Dependence	
All	6.58

JHK Model, Temp Dependence, Constrained



Probabilistic Approach to Creep Modeling

Md Abir Hossain

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)

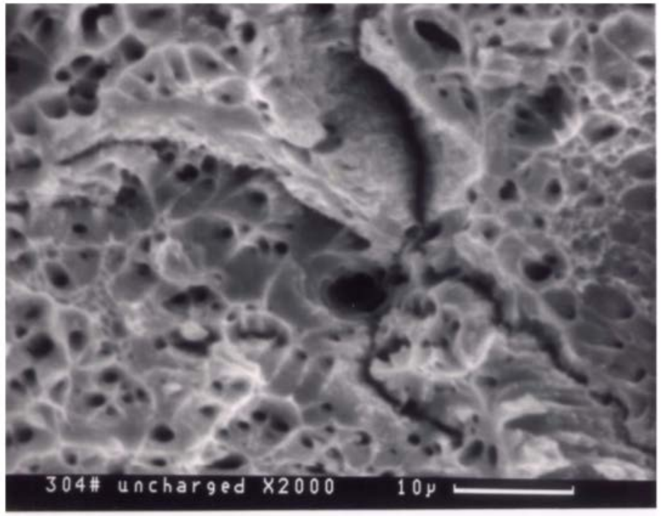
List of Publication

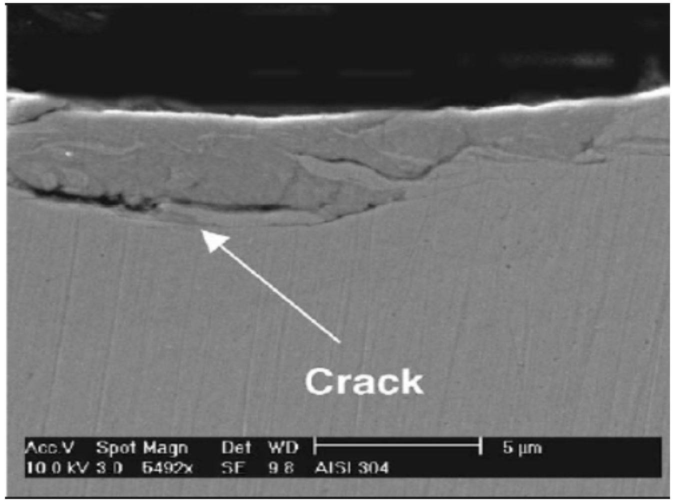
- Hossain, M.A., and Stewart, C.M., 2019, “Reliability Prediction of Sine-Hyperbolic Creep-Damage Model using Monte Carlo Simulation Method,” ASME PVP 2019, San Antonio, Texas, July 14 – 19, 2019.
- Hossain, M. A., and Stewart C.M., 2019, “Probabilistic Evaluation of 304 Stainless Steel using Sine Hyperbolic Creep-Damage Model,” SETS 2019, EL Paso, TX, March 26-27, 2019.

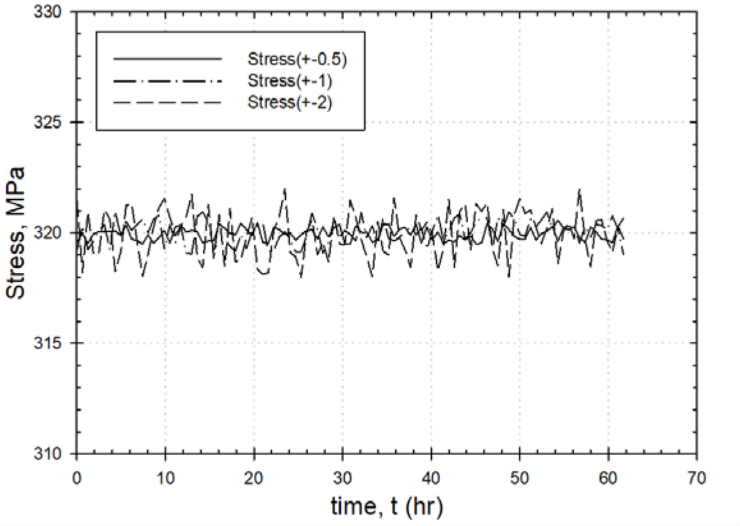
Sources of Uncertainty

The Reliability of Creep Behavior

- Uncertainty of Material Constants
- Uncertainty of pre-existing Defects
- Uncertainty of Service Condition $\Delta\sigma(t), \Delta T(t)$







Sine-Hyperbolic Creep-Damage Model

The coupled creep-damage Sinh constitutive model used in this study consisting of creep strain rate and damage evolution equations are as follow

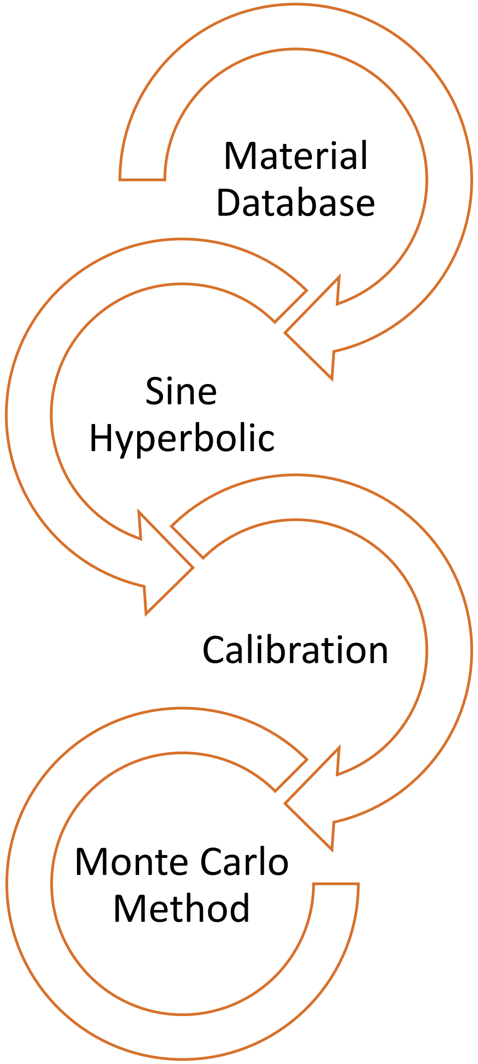
$$\dot{\varepsilon}_{cr} = A\sinh\left(\frac{\sigma}{\sigma_s}\right)\exp(\lambda\omega^{3/2})$$

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

Material Constant	Behavior
A	Secondary Creep coefficient
M	Accommodates temperature dependency
σ_s	Mechanism Transition Stress
σ_t	Mechanism transition stress
ϕ	Controls the trajectory
λ	Dictates the slope of creep curves

Uncertainty Analysis of Creep-Damage Model

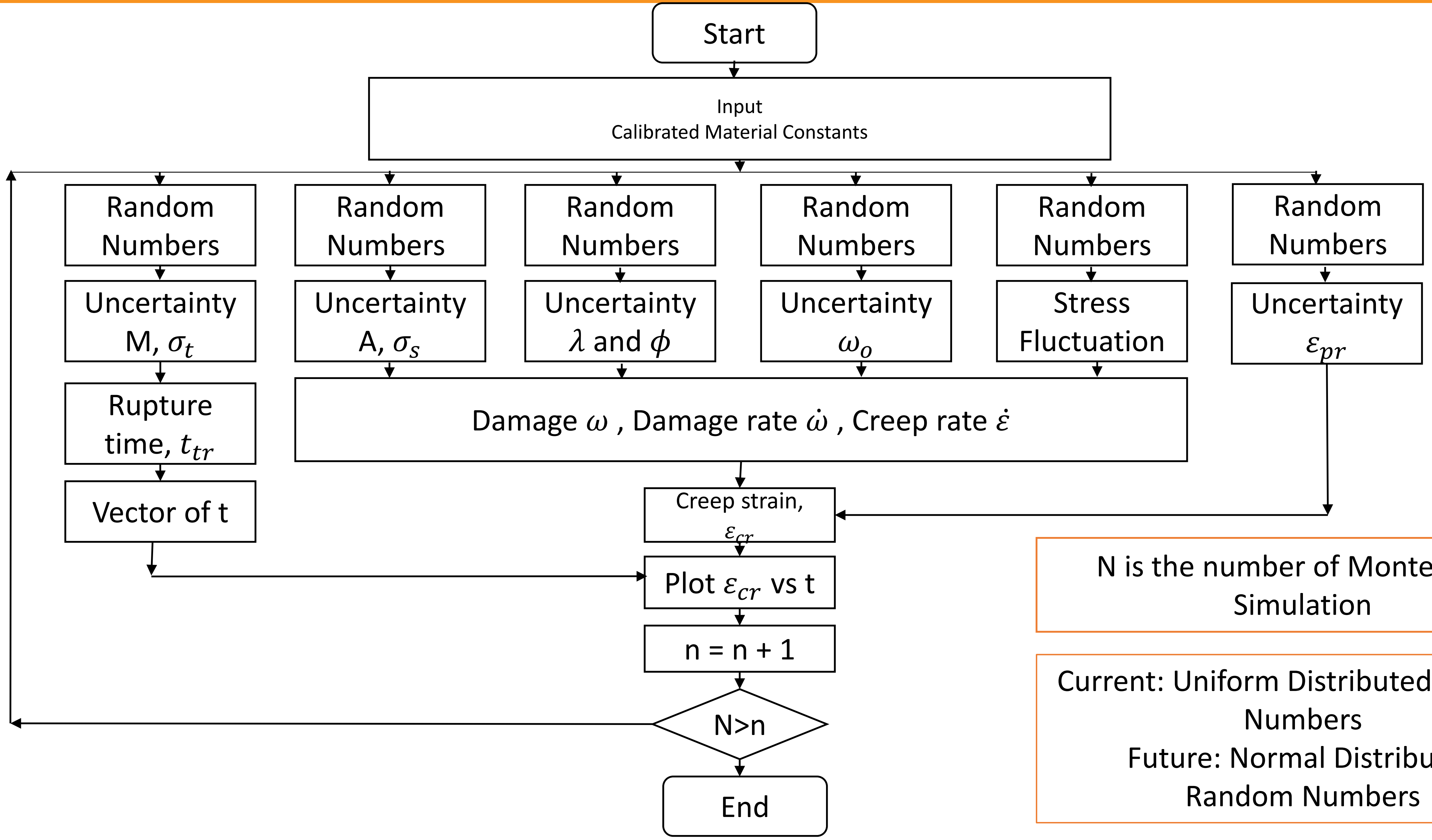
- Experimental creep deformation data for 304 Stainless Steel with 10 replicated test at each temperature state was adopted from the material database.
- Sine-Hyperbolic creep-damage model has been selected for integrating the probabilistic feature because of the ease of calibration and implementation 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

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

SCRI Model



Start

Input
Calibrated Material Constants

Random Numbers

Uncertainty M, σ_t

Rupture time, t_{tr}

Vector of t

Random Numbers

Uncertainty A, σ_s

Random Numbers

Uncertainty λ and ϕ

Random Numbers

Uncertainty ω_o

Random Numbers

Stress Fluctuation

Random Numbers

Uncertainty ε_{pr}

Damage ω , Damage rate $\dot{\omega}$, Creep rate $\dot{\varepsilon}$

Creep strain, ε_{cr}

Plot ε_{cr} vs t

n = n + 1

N>n

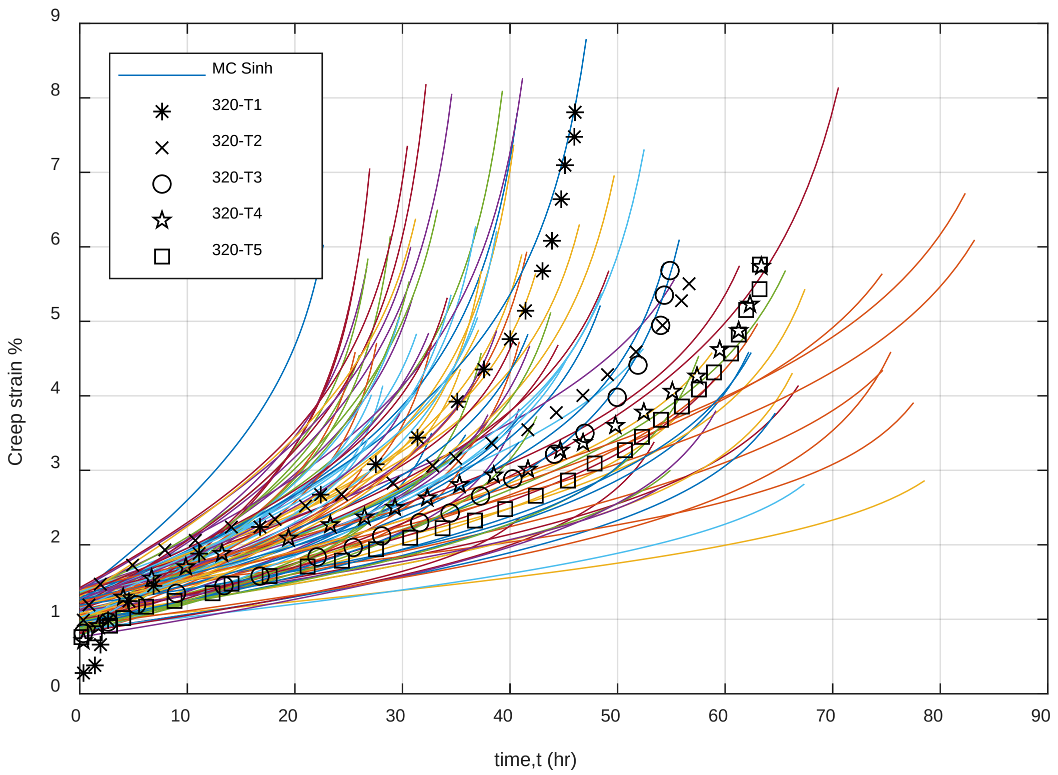
End

N is the number of Monte Carlo Simulation

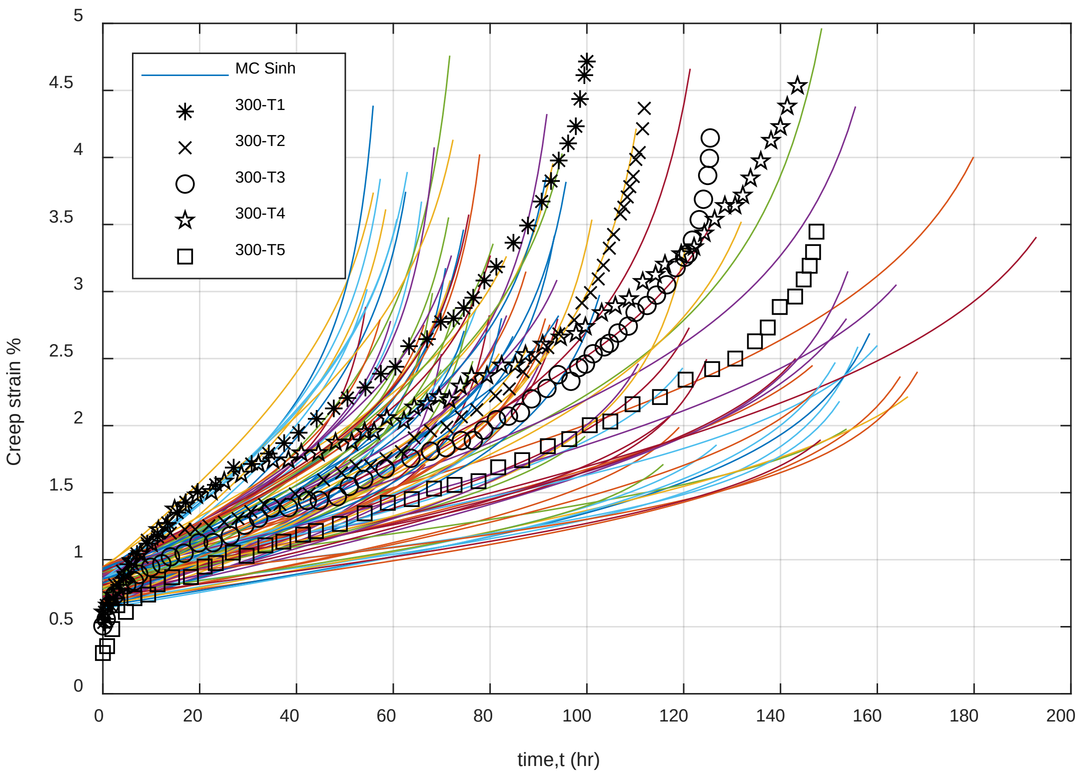
Current: Uniform Distributed Random Numbers
Future: Normal Distributed Random Numbers

Predicted Creep Deformation Curves

At 600 °C subjected to 320 MPa



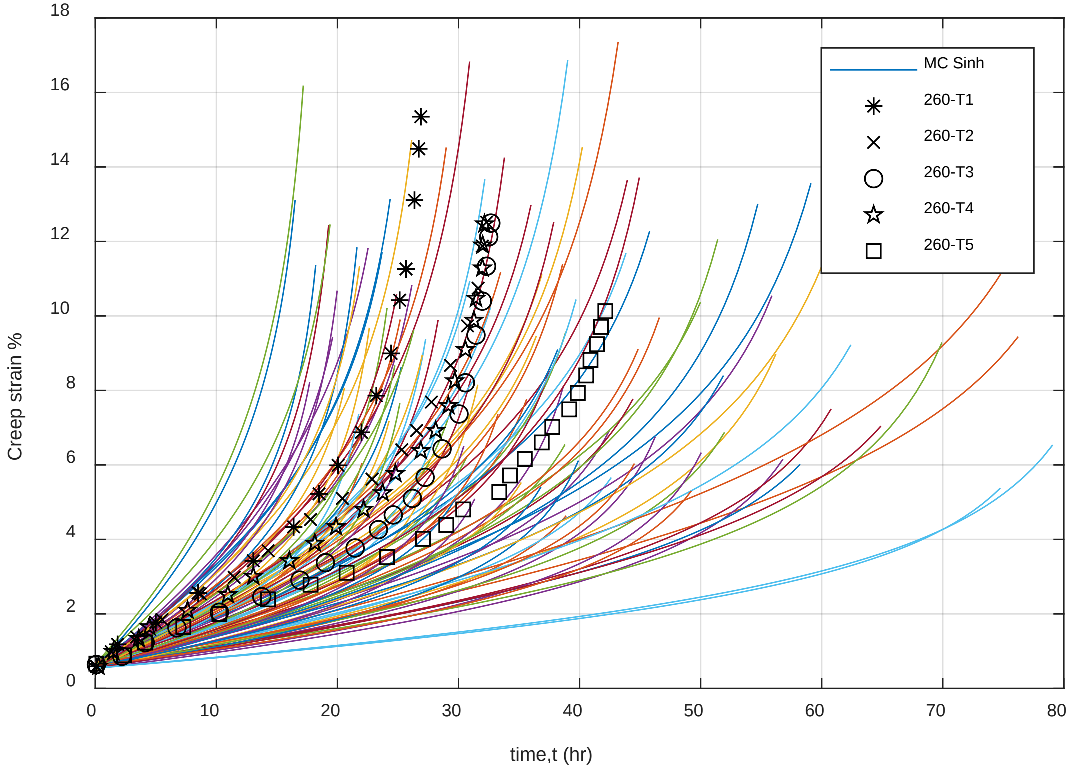
At 600 °C subjected to 300 MPa

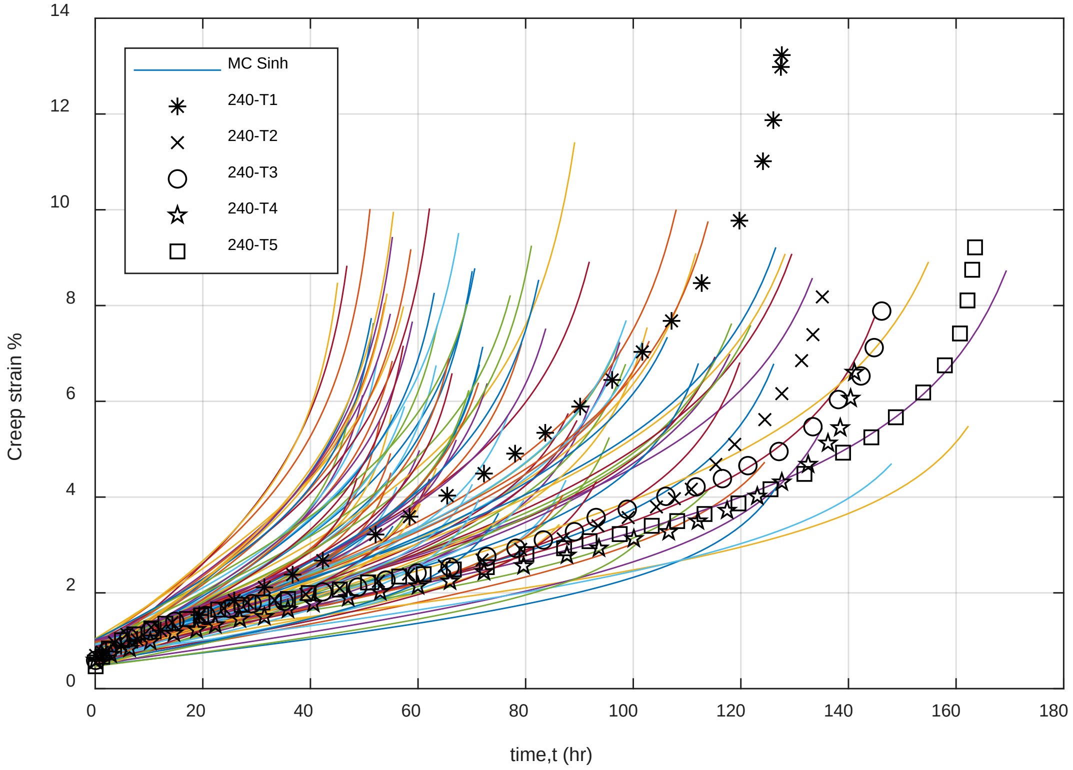


Predicted Creep Deformation Curve

At 650 °C subjected to 260 MPa

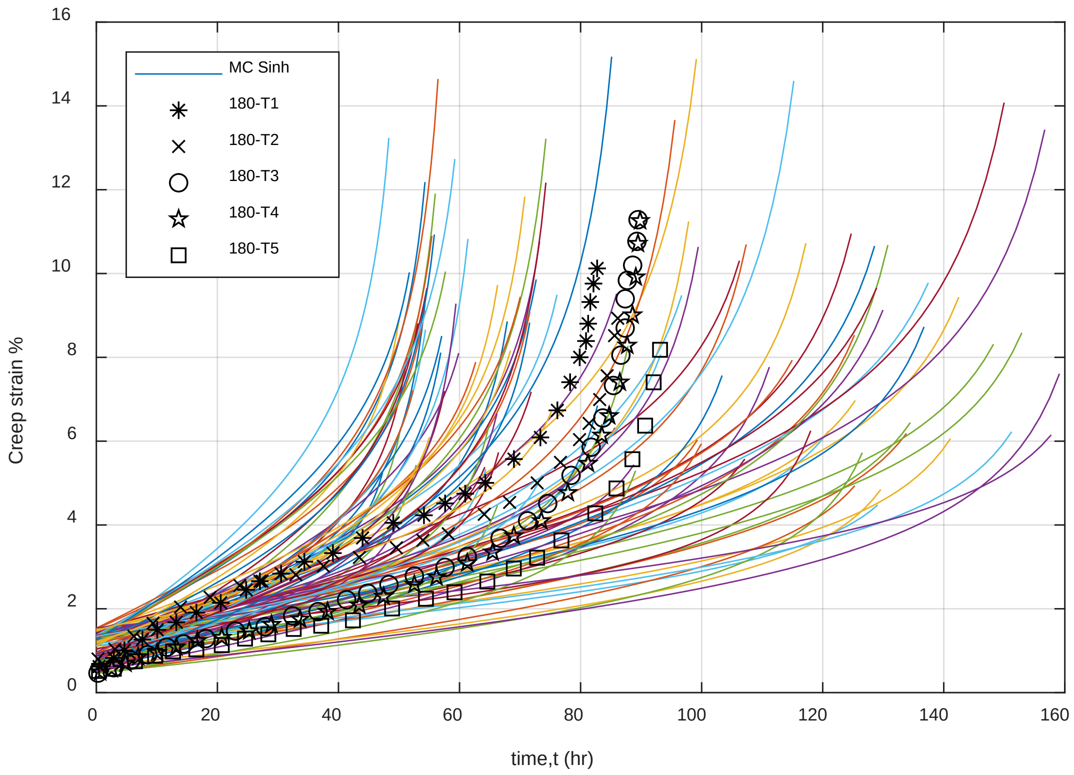
At 650 °C subjected to 240 MPa



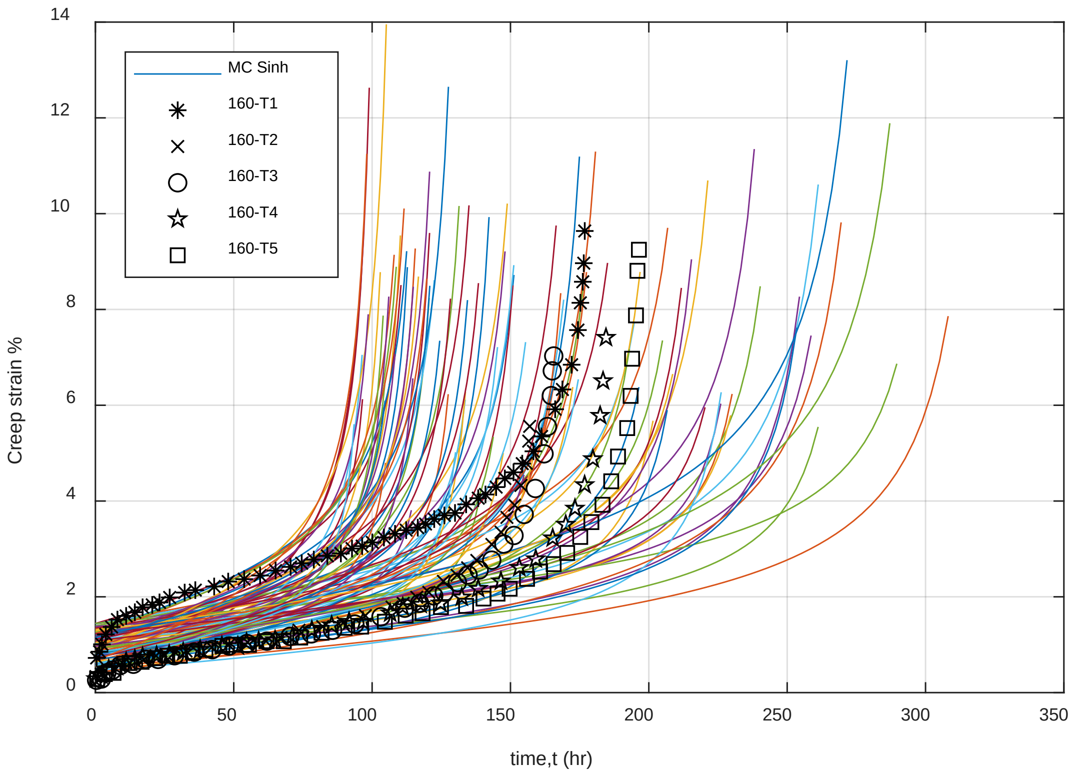


Predicted Creep Deformation Curves

At 700 °C subjected to 180 MPa

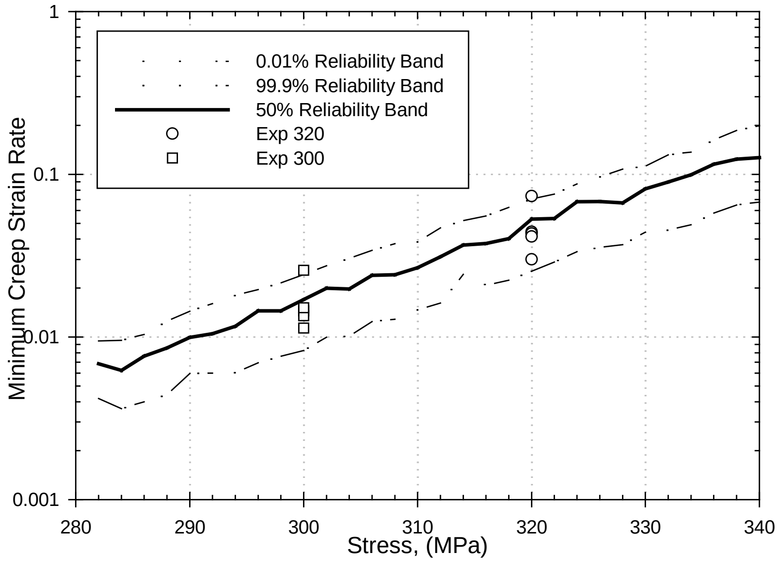


At 700 °C subjected to 160 MPa

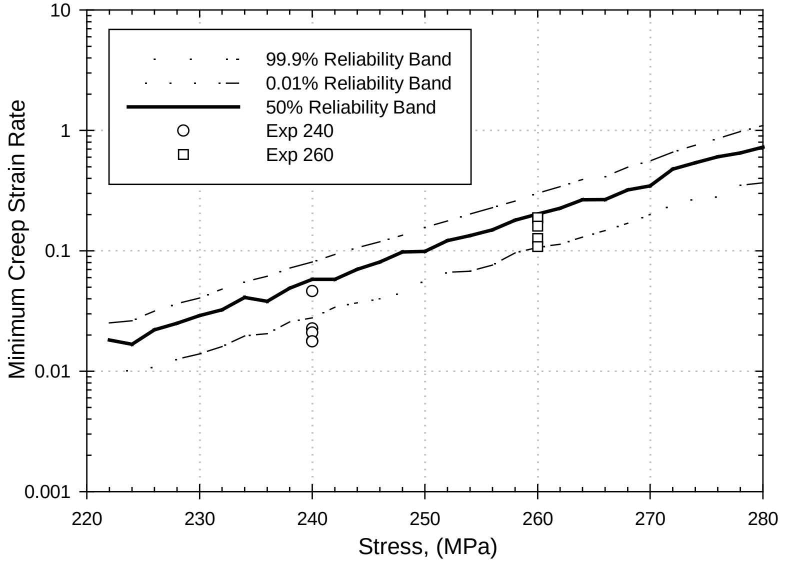


Reliability Bands for MCSR

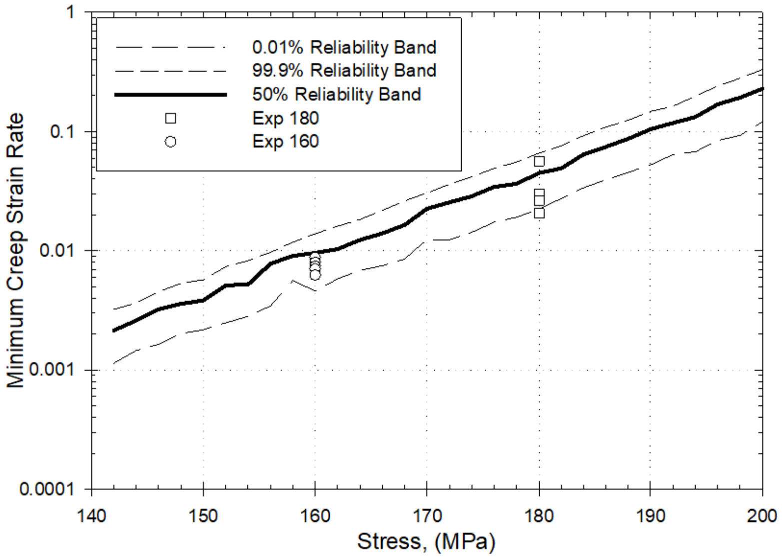
MCSR Bands at 600 °C



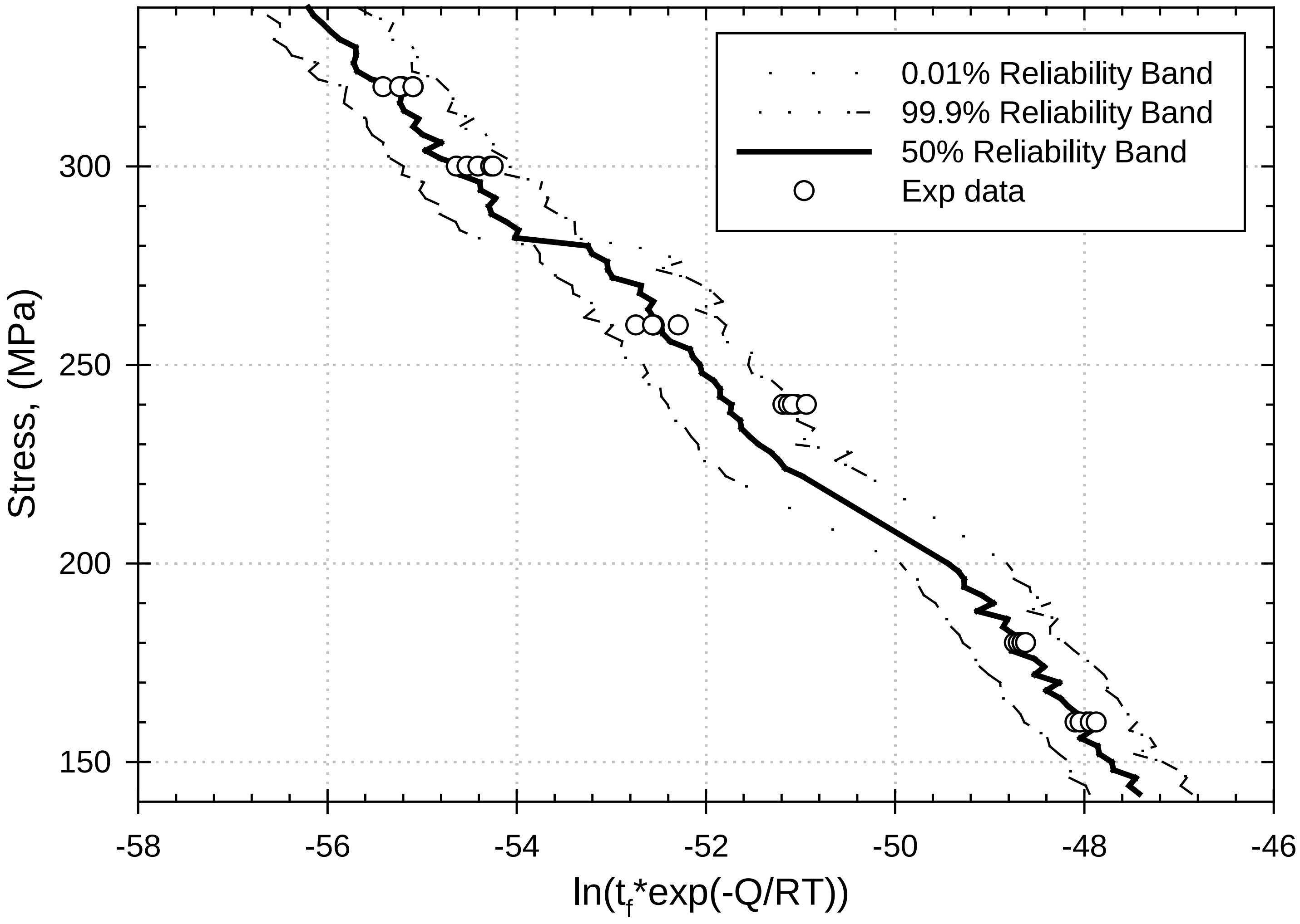
MCSR Bands at 650 °C



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.

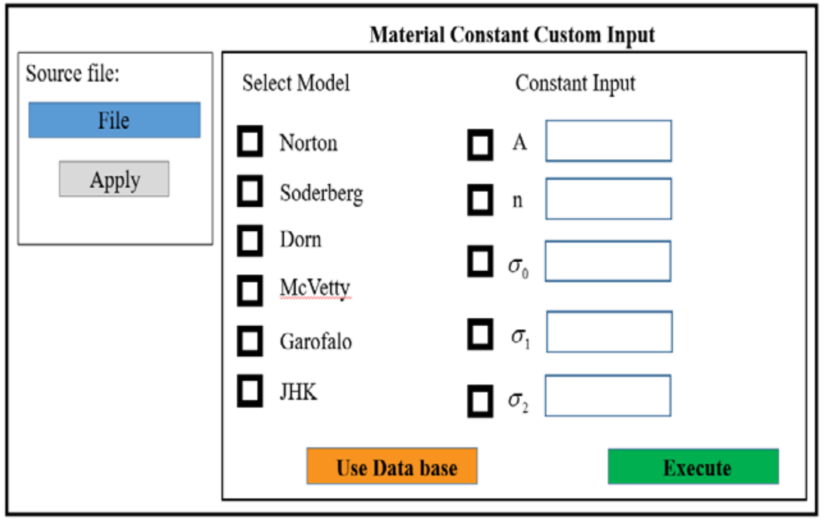
- Integration of the probabilistic modeling in the commercial FEM software will help in simulating event which might cause catastrophic failure such as failure of a turbine blade.

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



Material Constant Custom Input

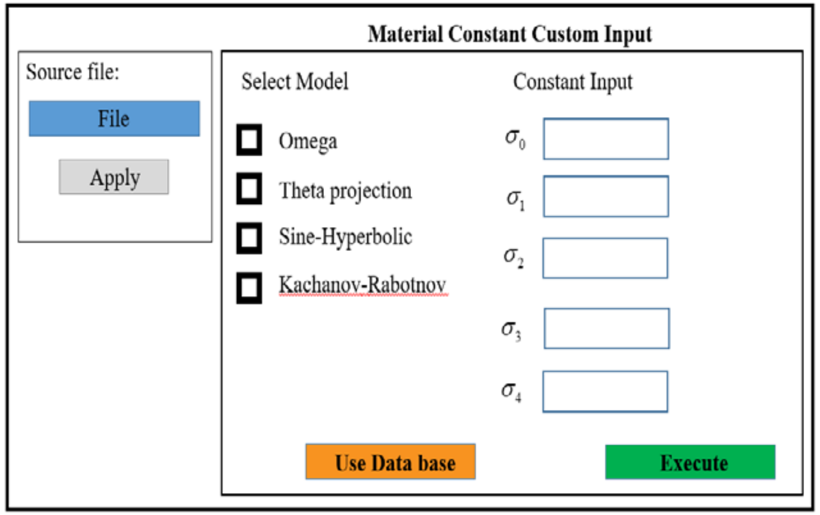
Source file:

Select Model

☐ Norton
☐ Soderberg
☐ Dorn
☐ McVetty
☐ Garofalo
☐ JHK

Constant Input

☐ A
☐ n
☐ σ_0
☐ σ_1
☐ σ_2



Material Constant Custom Input

Source file:

Select Model

☐ Omega
☐ Theta projection
☐ Sine-Hyperbolic
☐ Kachanov-Rabotnov

Constant Input

σ_0
σ_1
σ_2
σ_3
σ_4

Global Optimization
MACHO
MAterial Constant Heuristic Optimization

ANSYS®

SIMULIA
ABAQUS

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

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QUESTION