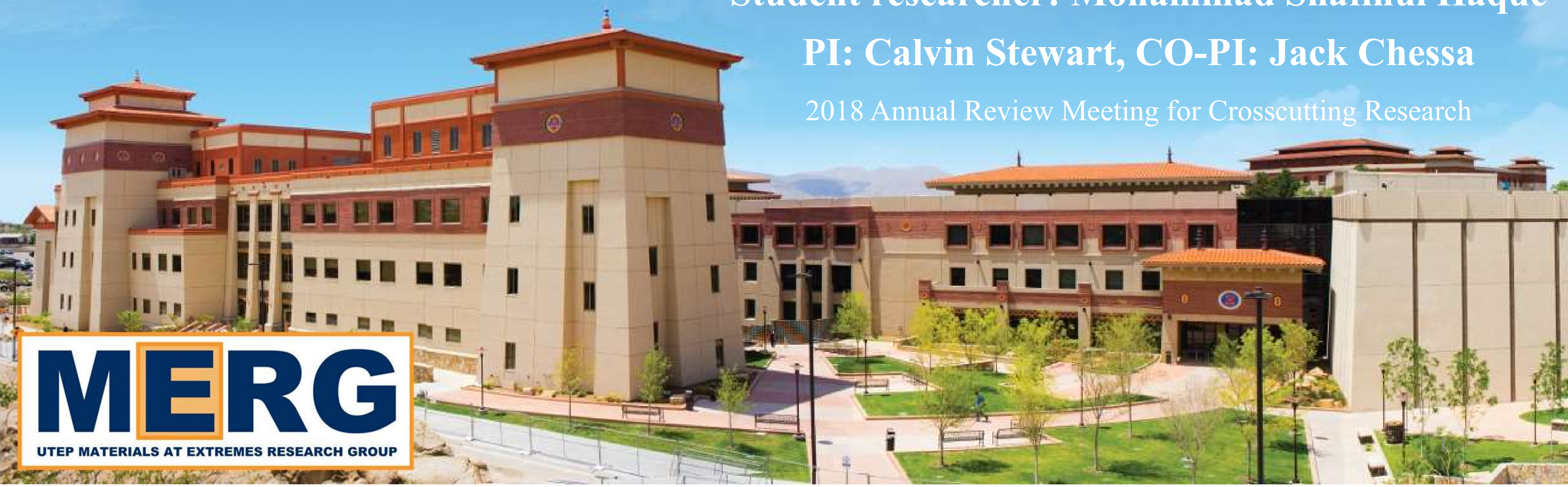
THE UNIVERSITY OF TEXAS AT EL PASO
COLLEGE OF ENGINEERING

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

Student researcher: Mohammad Shafinul Haque

PI: Calvin Stewart, CO-PI: Jack Chessa

2018 Annual Review Meeting for Crosscutting Research



MERG
UTEP MATERIALS AT EXTREMES RESEARCH GROUP

Outline

Motivation

Research Objectives

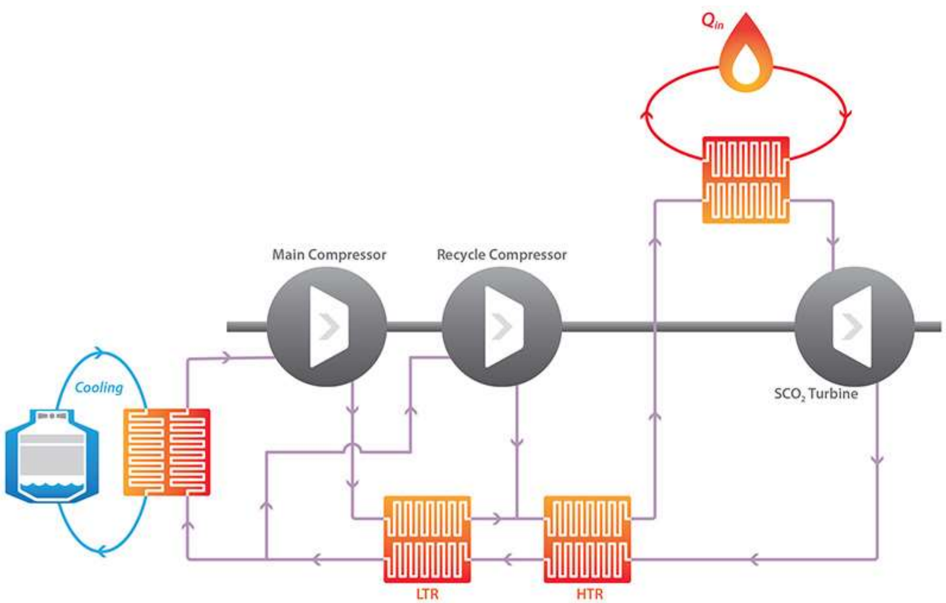
Systematic Approach to Assessment

Results and Accomplishments

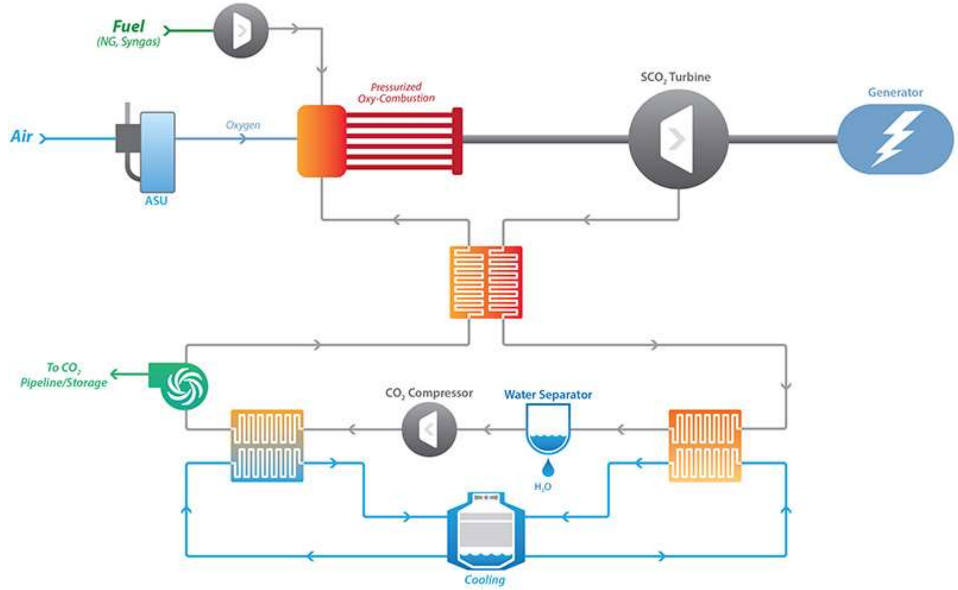
Summary

Motivation

- 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

Figures via NETL

Motivation

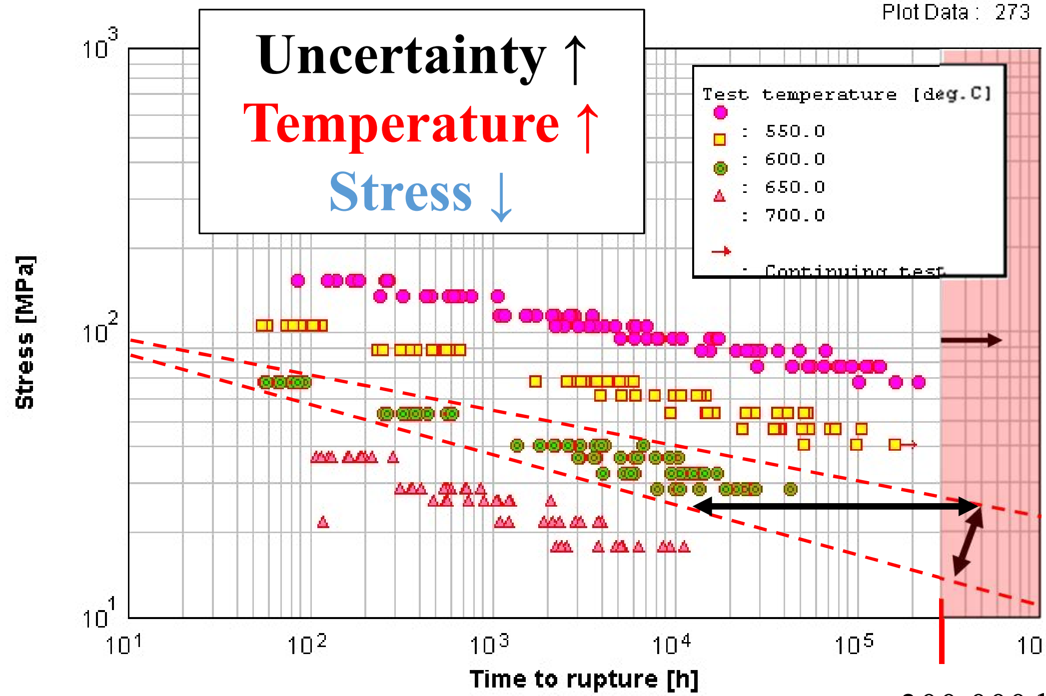
- The existing FE fleet has an **average age of 40 years**.
- The Department of Energy has outlined a strategy of life extension for US coal-fired power plants where many plants will operate for **up to 30 additional years of service**.

In Service Hours….

30 Years = 262,974 hours

40 Years = 350,634 hours

70 Years = 613,607 hours

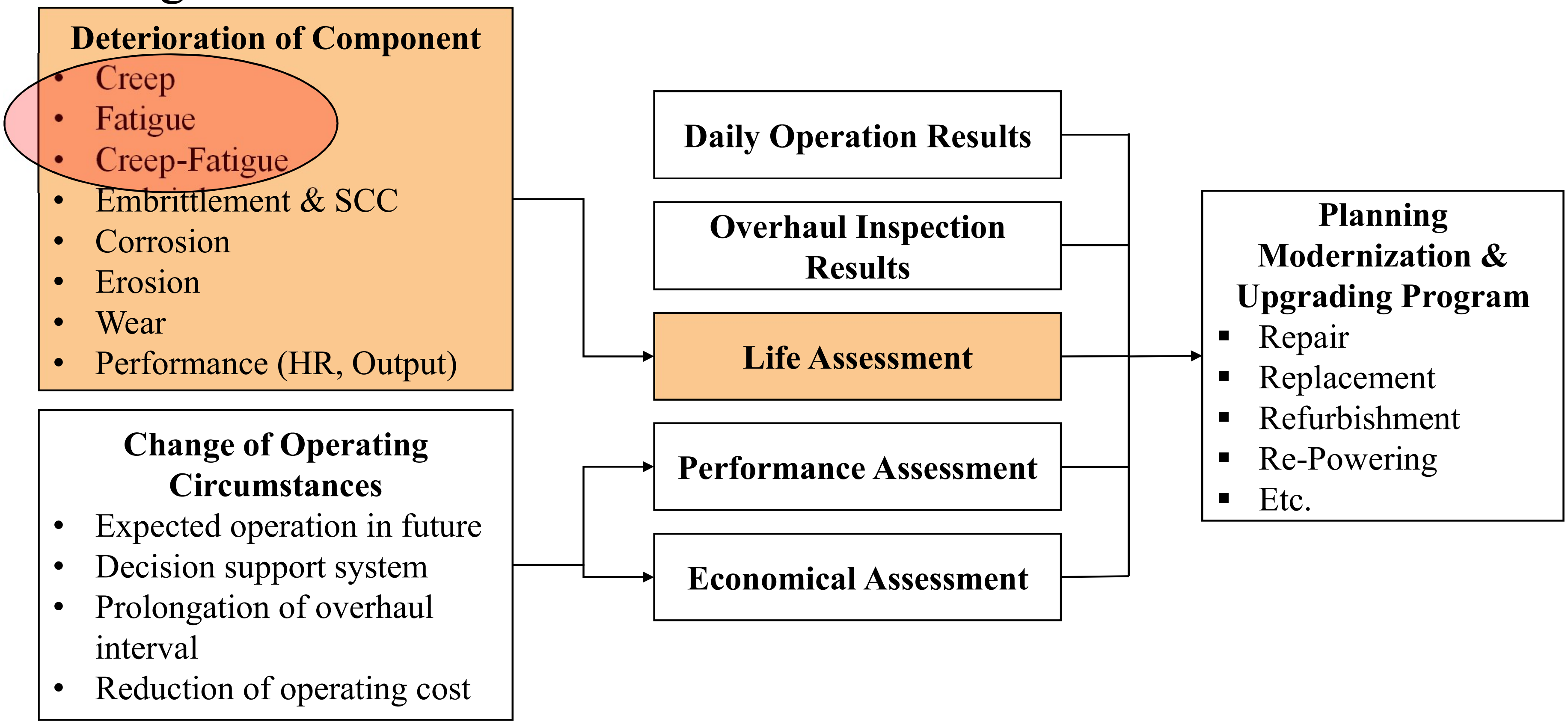


300,000 hours

Creep-Rupture of 9Cr-1Mo Tube

Plant Life Extension Program

- During Life Assessment, the integrity of components is assessed and the remaining service life estimated.



Based on Mitsubishi's Life Extension Program

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.

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!…

Research Objectives

- 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	**RO2**
Development of **Aggregated Experimental Databases** of Creep and Creep-Fatigue Data	**Computational Validation and Assessment** of Creep and Creep-Fatigue Constitutive Models for Standard and Non-Standard Loading Conditions

The Team

Calvin M Stewart, Project PI

Jack F Chessa, Project Co-PI

Mohammad Shafinul Haque
(**PhD, Spring 2018**)

Christopher Ramirez
(MS, Graduated 2017)

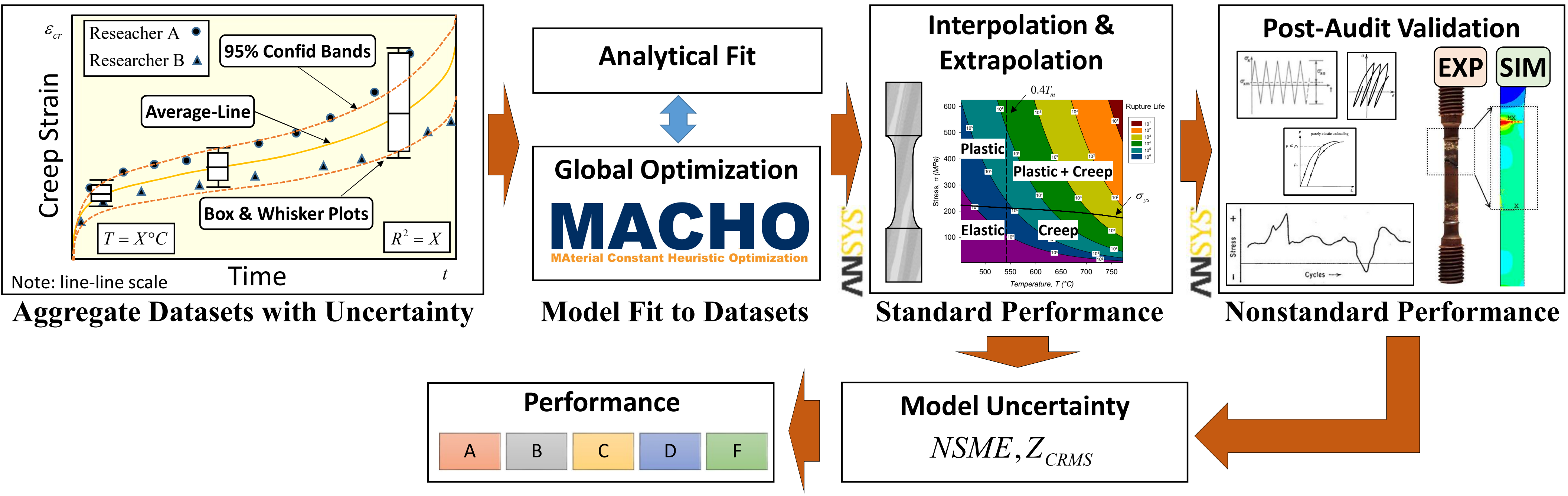
Jimmy Perez
(MS)

Amanda Haynes
(UG, ACT program)

Ricardo Vega
(Undergrad)

Systematic Approach to Assessment

Example for Creep Deformation



Systematic Approach to Assessment

Task 1: Locate, Digitize, Sort, Store Experimental Data

Task 2: Uncertainty and Integrity of Experimental Database

Task 3: Mathematical Analysis and FEA of the Models

Task 4: Calibration & Validation – Fit, Interpolation, Extrapolation of the Models

Task 5: Post-Audit Validation of the Models

Task 6: Disparate Data problem and Design Maps

Task 7: Metamodeling: Finding the "best" model

Task 8: Multiaxial Representative Function

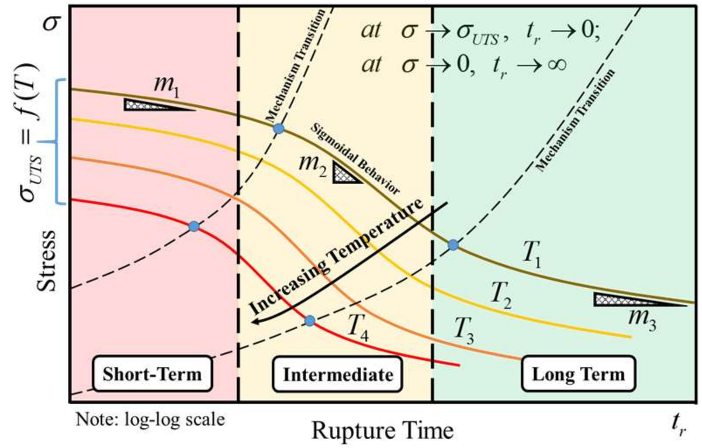
Task 1: Locate, Digitize, Sort, and Store Data

Creep Data

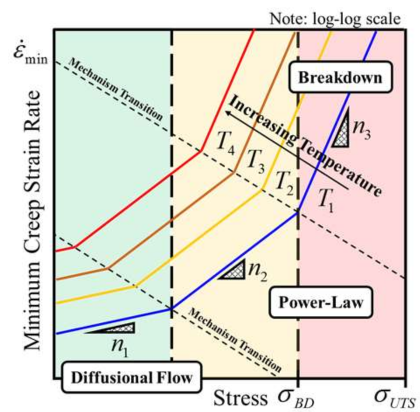
- Creep-rupture
- Minimum creep strain rate
- Time to creep strain
- Creep deformation
- Stress relaxation

Creep-Fatigue Data

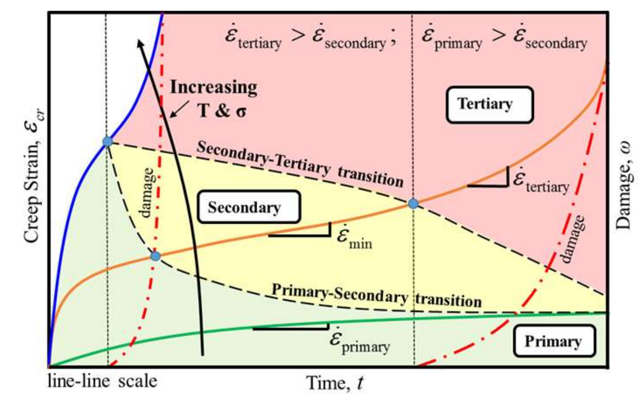
- Tensile Hold Tests



Ideal creep rupture curve

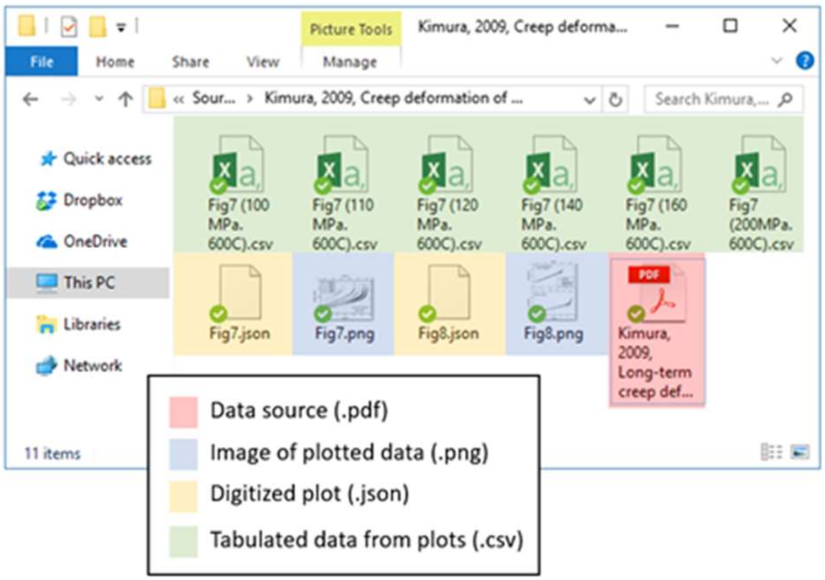


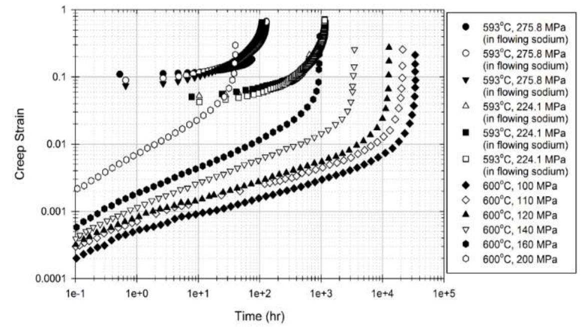
Ideal minimum creep strain rate curve

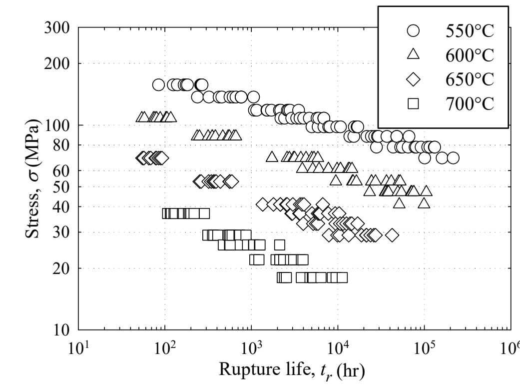


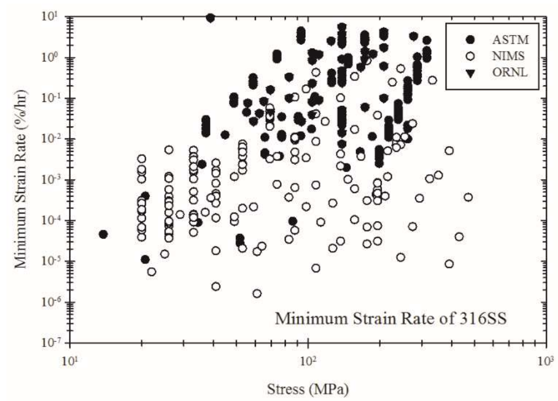
Ideal creep deformation and damage evolution

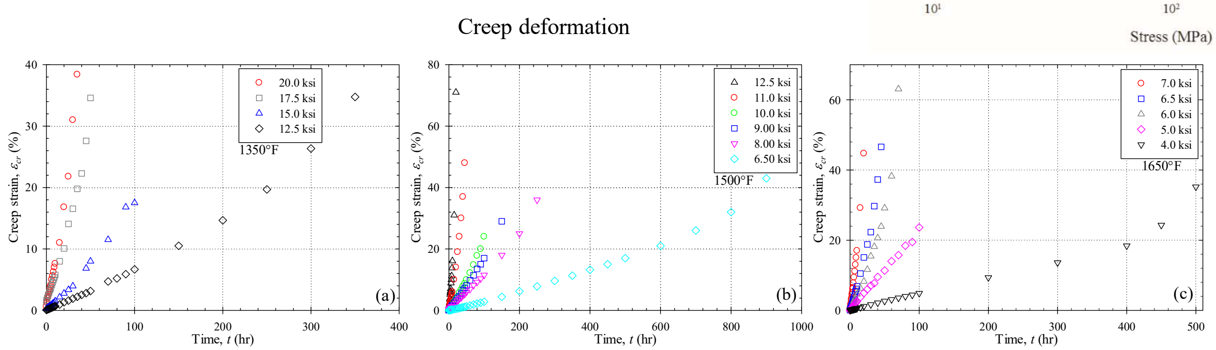
Task 1: Locate, Digitize, Sort, and Store Data

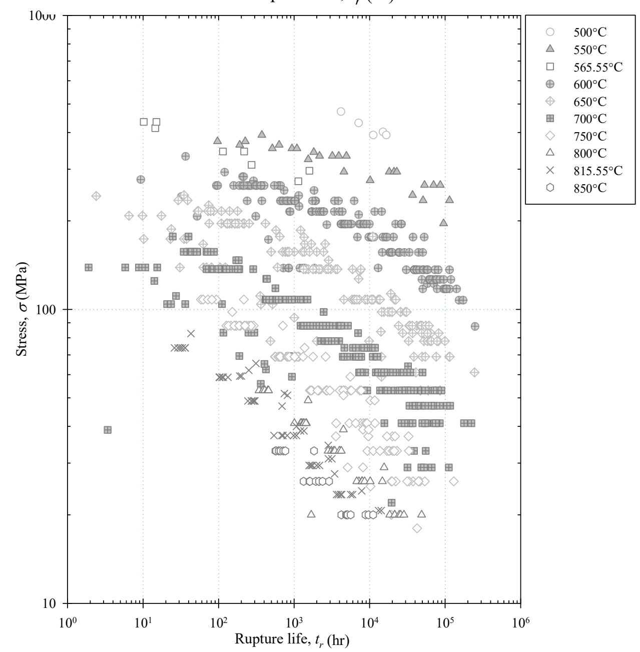










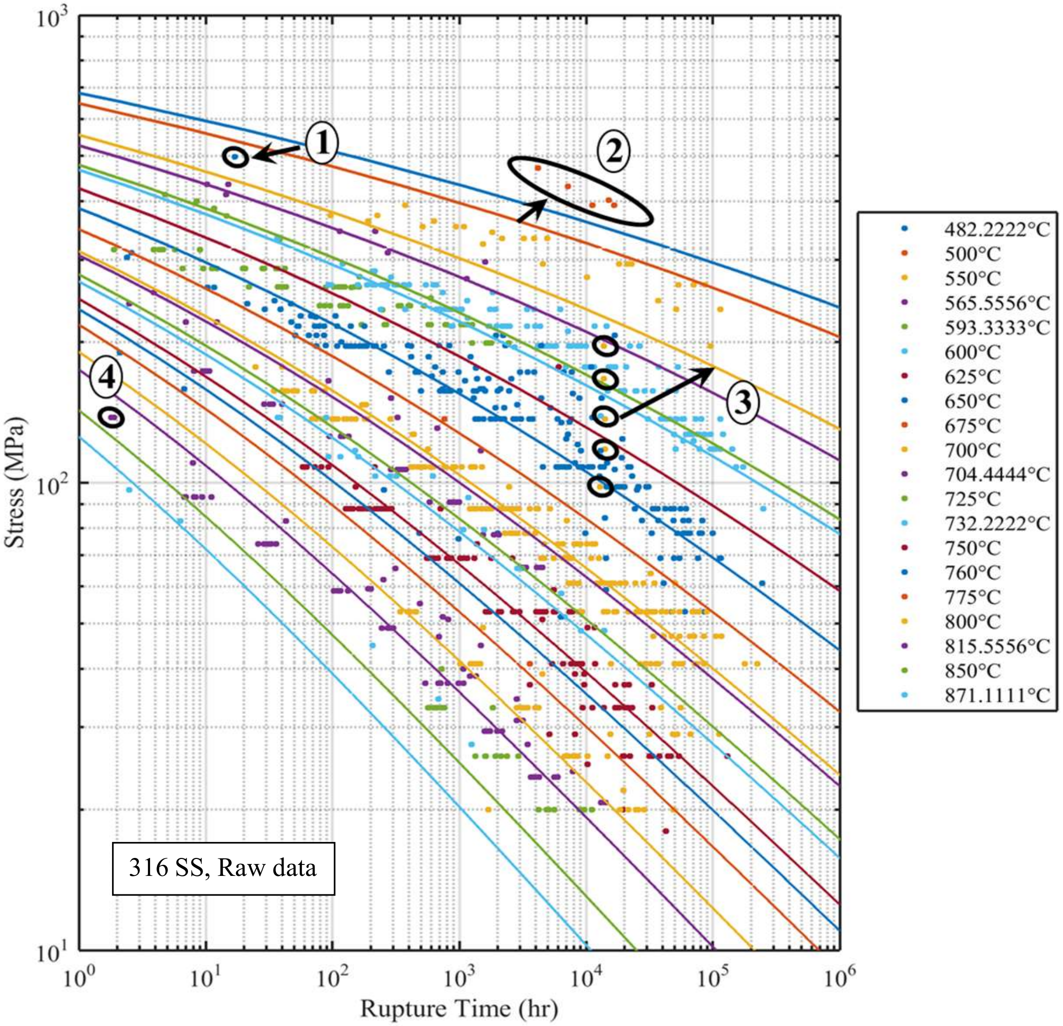


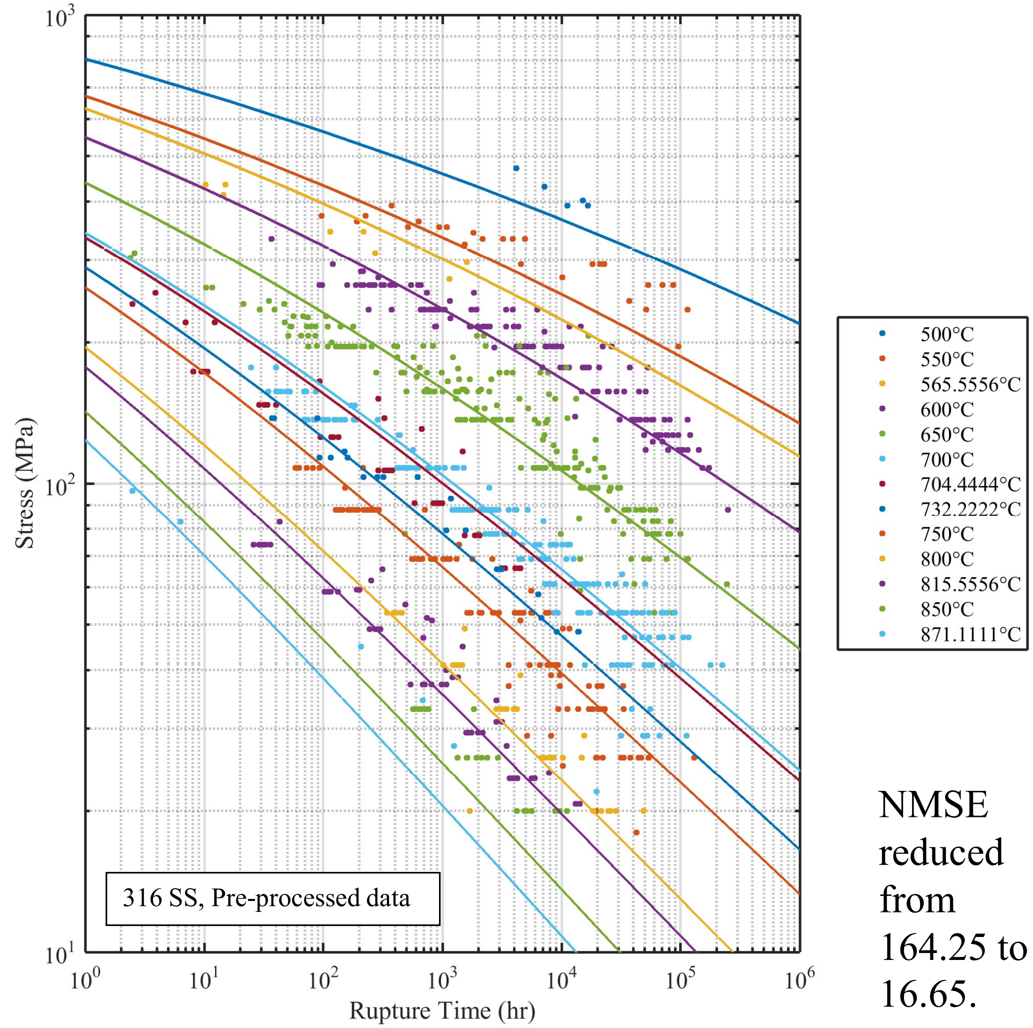
Task 1: Locate, Digitize, Sort, and Store Data

Table 3 – Data collected by data source

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						

Task 2: Uncertainty Analysis (Data Pre-processing)





NMSE reduced from 164.25 to 16.65.

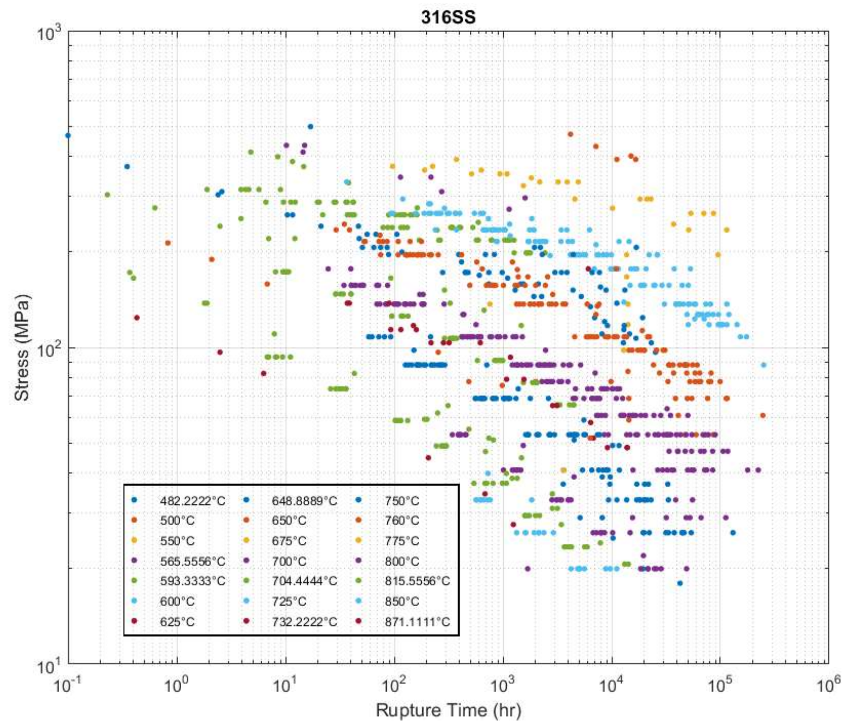
Task 2: Uncertainty Analysis (Metadata)

- **Metadata** include: form, thermomechanical processing, source, chemistry, geometry, laboratory code, etc.

Form	Data points
Bar	438
Bar and Plate	17
Pipe	9
Plate	210
Tube	321

Source	Data points
ASTM DS5-S1	289
ASTM STP 552	9
NIMS online database	697

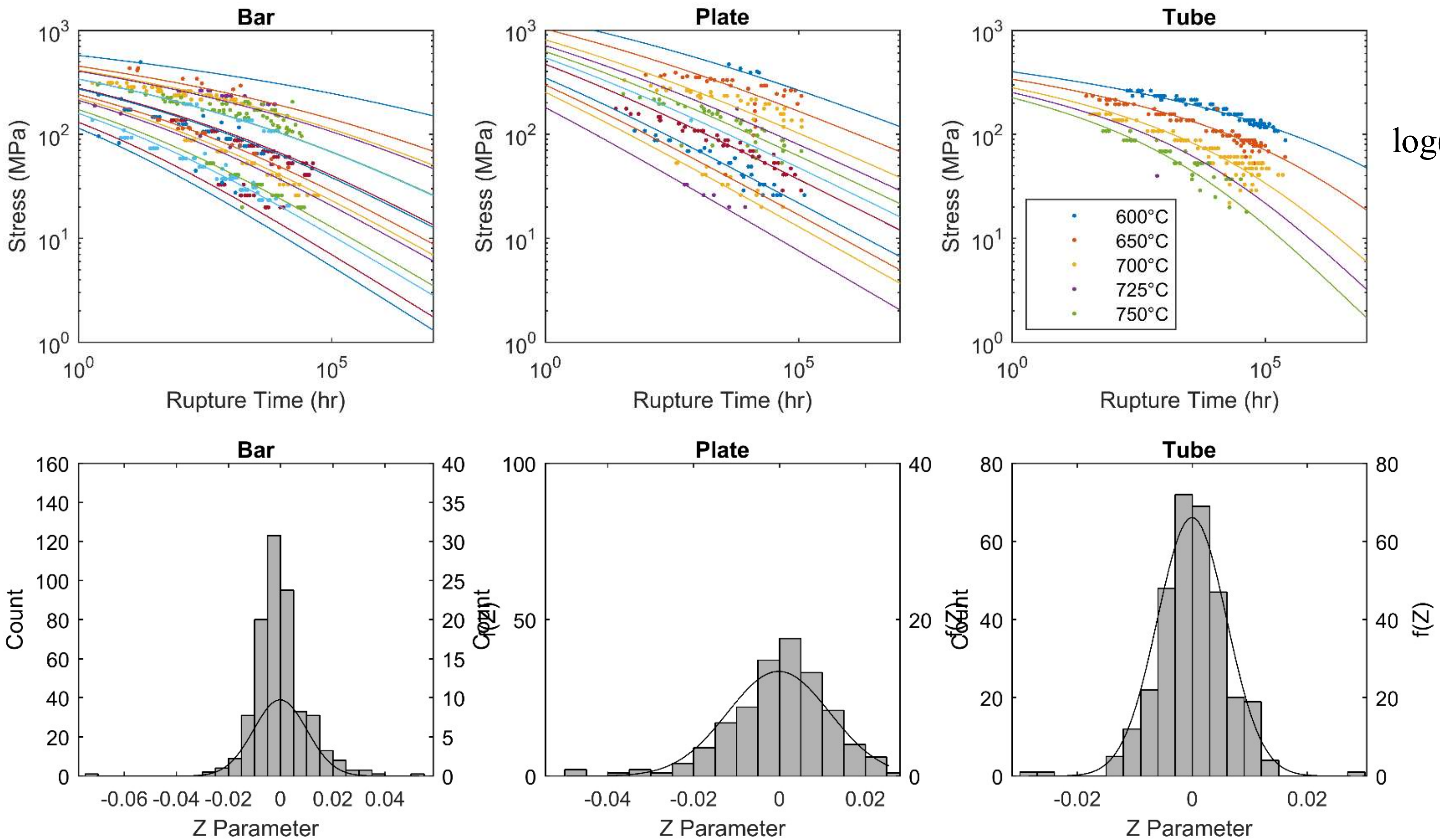
Processing	Data points
Annealed	11
Forged	19
Hot extruded	9
Hot extruded and cold drawn	167
Hot rolled	520
Quenched	115
Rotary pierced and cold drawn	154



Combined data

Ref: Ramirez. C., Haque, M. S., and Stewart, C. M. (2017). Guidelines To The Assessment Of Creep Rupture Reliability For 316SS Using The Larson-miller Time-temperature Parameter Model. ASME Pressure Vessel and Piping Conference. Paper No. PVP2017-65816.

Data parsing

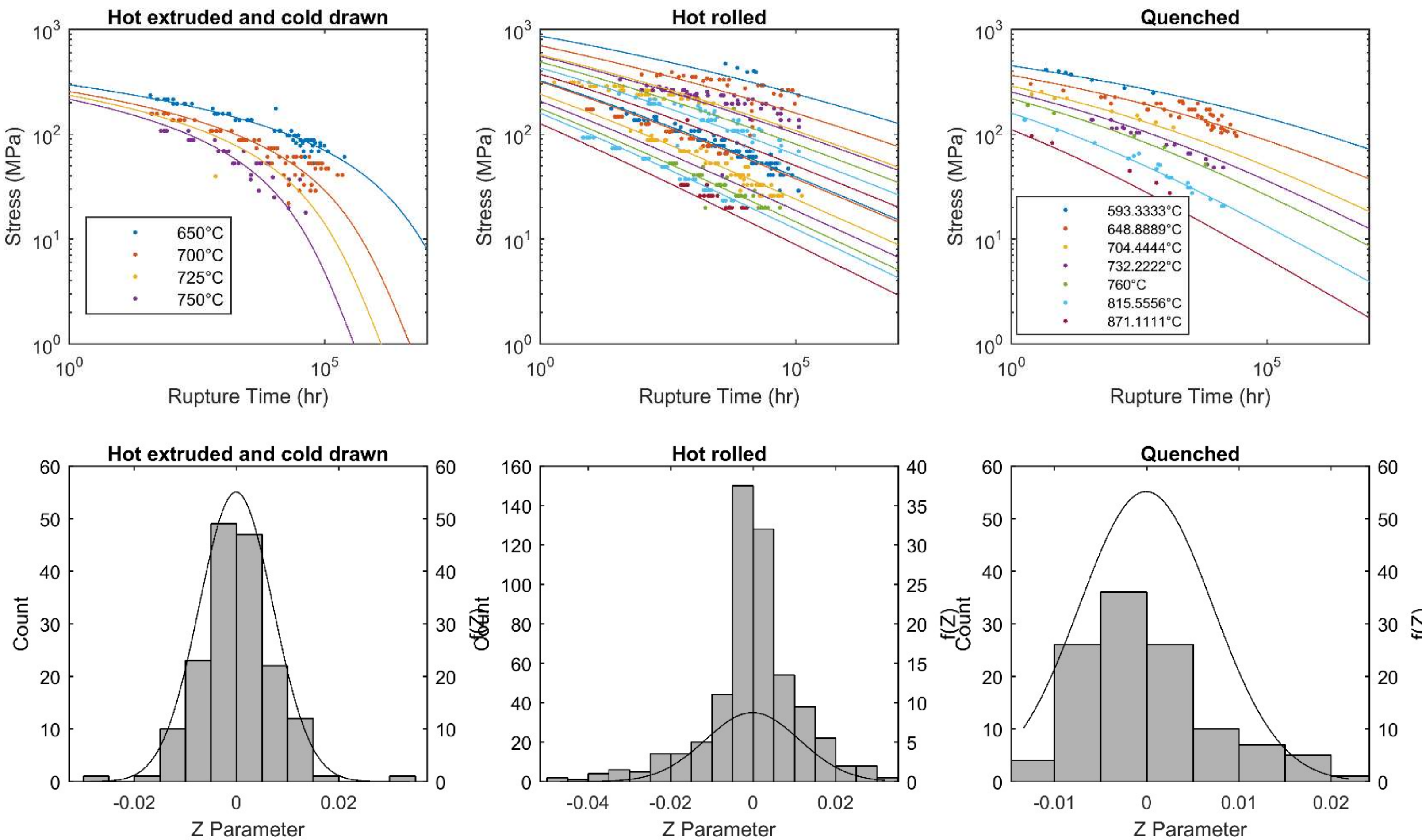


$$Z = t_{r,exp} - t_{r,LMP}$$

$$\log(Z) = \log(P_{exp}) - \log(P_{LMP})$$

Rupture Prediction (100MPa, 500°C)	
Form	**Rupture time (hrs)**
Bar	6.77E7
Plate	2.57E7
Tube	28.2E7

Data parsing



Rupture Prediction (100MPa, 500°C)	
TMP	**Rupture time (hrs)**
HE & CD	14.5E7
HR	5.05E7
Quenched	105E9

Data Cull

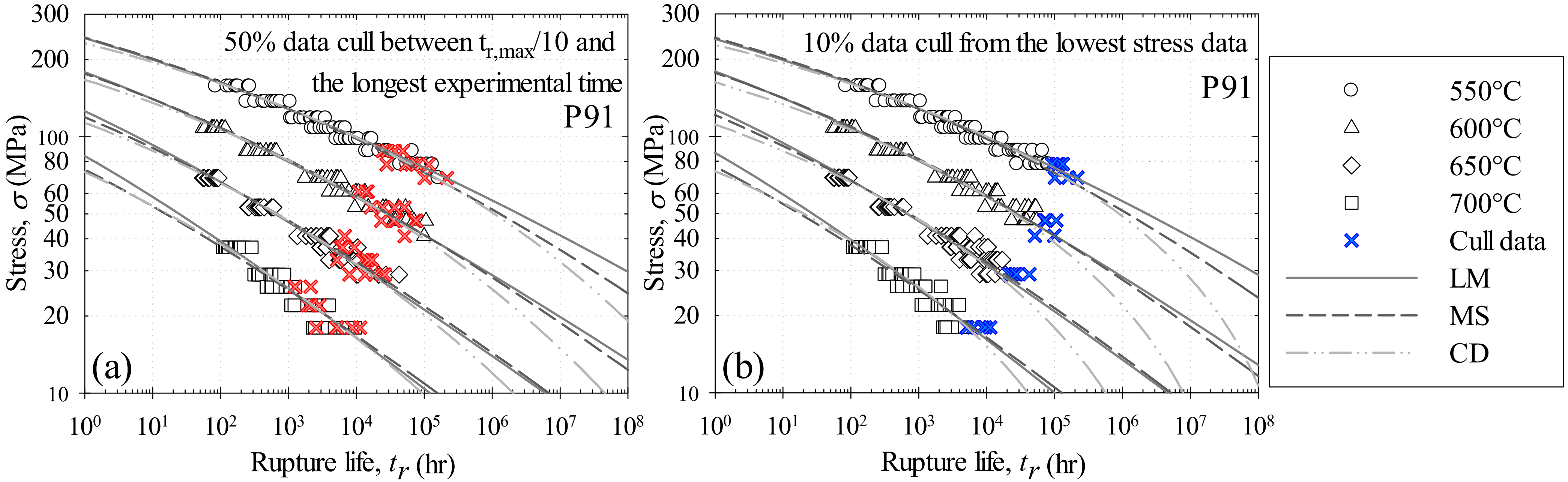


Figure – Rupture prediction of LM, MS, and CD against (a) 50% data cull between $t_{r,\max}/10$ and the longest time and (b) 10% data cull from the lowest stress data

Task 3: Mathematical Analysis

Stress-Rupture

- **Eight** commonly used TTP models
- **Four** newly developed model

Creep-deformation

- Omega model
- Theta Projection

Minimum Strain rate

- Norton Power Law
- McVetty Law
- **Four** additional model

Continuum Damage Mechanics

- Kachanov-Rabotnov
- Sin-hyperbolic
- Liu-Murakami

Multiaxial Representative Stress Functions

- Hayhurst
- Huddlestone
- Additional **five** model

Rupture, Deformation, and Steady-state models

Table: Creep-Rupture Models

Model	Year	Parametric equation
Larson-Miller	1952	$P_{LMP} = T(\log(t_r) + t_a)$
Manson-Haferd	1953	$P_{MH} = \frac{\log(t_r) - \log(t_a)}{T - T_a}$
Manson-Brown	1953	$P_{MB} = \frac{\log(t_r) - \log(t_a)}{(T - T_a)^n}$
Orr-Sherby-Dorn	1954	$P_{OSD} = \log(t_r) - Q / RT$
Manson-Succop	1959	$P_{MS} = \log(t_r) - BT$
Graham-Walles	1955	$P_{GW} = \frac{\log(t_r)}{(T - T_a)^n}$
Chitty-Duval	1963	$P_{CD} = mT - \log(t_r)$
Goldhoff-Sherby	1968	$P_{GS} = \frac{\log(t_r) - \log(t_a)}{1/T - 1/T_a}$
Modified Manson-Haferd	--	$P_{MMH} = \frac{\log(t_r) - \log(t_a)}{T}$
Modified Graham-Walles	--	$P_{MGW} = \frac{\log(t_r)}{(1/T - 1/T_a)^n}$
Modified Chitty-Duval	--	$P_{CD} = \frac{m}{T} - \log(t_r)$
Modified-Goldhoff-Sherby	--	$P_{GS} = \frac{\log(t_r) - \log(t_a)}{(1/T - 1/T_a)^n}$

Table: Creep deformation

Omega model

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

$$\dot{\varepsilon}_t = \theta_3 \theta_4 \exp(\theta_4 t)$$

Theta model

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \exp(\varepsilon \Omega)$$

$$\omega = \frac{t}{t_r} = \frac{\dot{\varepsilon} \Omega t}{1 + \dot{\varepsilon} \Omega t}$$

Table: Minimum-creep-strain-rate model

Source	Creep law
Norton, 1929	$\dot{\varepsilon}_{cr} = A(\sigma / \sigma_0)^n$
Soderberg, 1936	$\dot{\varepsilon}_{cr} = A\{\exp(\sigma / \sigma_0) - 1\}$
McVetty, 1943	$\dot{\varepsilon}_{cr} = A \sinh(\sigma / \sigma_0)$
Dorn, 1955	$\dot{\varepsilon}_{cr} = A \exp(\sigma / \sigma_0)$
JHK, 1963	$\dot{\varepsilon}_{cr} = A_1(\sigma / \sigma_0)^{n_1} + A_2(\sigma / \sigma_0)^{n_2}$
Garofalo, 1965	$\dot{\varepsilon}_{cr} = A\{\sinh(\sigma / \sigma_0)\}^n$

Figure: Turbine blade inspection

CDM models

Strain rate and Min. Strain rate	Damage Rate and Rupture Life
Kachanov-Rabotnov (KR) model	
$\dot{\varepsilon}_{cr} = A\left(\frac{\sigma}{1-\omega}\right)^n$	$\dot{\omega} = \frac{M_K \sigma^{\chi}}{(1-\omega)^{\phi_K}}$
$\dot{\varepsilon}_{\min} = A\sigma^n$ $A,\ n =$ Norton power law constants	$t_r = [(\phi_K + 1) M_K \sigma^{\chi}]^{-1}$ $M_K, \chi, \phi_K =$ tertiary creep damage constants
Liu-Murakami (LM) model	
$\dot{\varepsilon}_{cr} = A\sigma^n \exp(\rho\omega^{3/2})$	$\dot{\omega} = \frac{M_L[1-\exp(-\phi_L)]}{\phi_L} \sigma^q \exp(\phi_L \omega)$
$\dot{\varepsilon}_{\min} = A\sigma^n$	$t_r = \left[M_L \sigma^q\right]^{-1}$
$\rho = (2n+2)/(\pi\sqrt{1+3/n})$	$M_L, q, \phi_L =$ tertiary creep damage constants
Sin-hyperbolic (Sinh) model	
$\dot{\varepsilon} = B\sinh(\sigma/\sigma_s)\exp(\lambda\omega^{3/2})$	$\dot{\omega} = \frac{M_S\left[1-\exp(-\phi_S)\right]}{\phi_s} \sinh\left(\frac{\sigma}{\sigma_t}\right)^{\chi} \exp(\phi_S \omega)$
$\dot{\varepsilon}_{\min} = B\sinh(\sigma/\sigma_s)$	$t_r = \left[M_S \sinh\left(\frac{\sigma}{\sigma_t}\right)^{\chi}\right]^{-1}$
$B, \sigma_S =$ secondary creep constants $\lambda = \ln(\dot{\varepsilon}_{final} / \dot{\varepsilon}_{\min})$	$M_S, \sigma_t, \phi_S =$ tertiary creep damage constants

Representative Stress Functions

Sodbyrev	$\sigma_{rep} = \alpha\sigma_1 + (1-\alpha)\sigma_{vm}, \quad 0 \le \alpha \le 1$
Hydrostatic	$\sigma_{rep} = 3\beta\sigma_m + (1-\beta)\sigma_{vm}, \quad 0 \le \beta < 1$
Hayhurst	$\sigma_{rep} = \alpha\sigma_1 + 3\beta\sigma_m + (1-\alpha-\beta)\sigma_{vm}$ $0 \le \alpha + \beta \le 1$

Dyson, Webster and Cane	$\sigma_{rep} = \left(\dfrac{\sigma_1}{\sigma_{VM}}\right)^{\gamma/\nu} \sigma_{VM}, \quad 0 \le \gamma \le \nu$
Hydrostatic	$\sigma_{rep} = \left(\dfrac{3\sigma_m}{\sigma_{VM}}\right)^{\gamma/\nu} \sigma_{VM}, \quad 0 \le \gamma < \nu$
Combined	$\sigma_{rep} = \left(\dfrac{\sigma_1}{\sigma_{VM}}\right)^{\gamma/\nu} \left(\dfrac{3\sigma_m}{\sigma_{VM}}\right)^{\mu/\nu} \sigma_{VM}, \quad 0 \le \gamma + \mu < \nu$

Huddleston	$\sigma_{rep} = \dfrac{3}{2} S_1 \left(\dfrac{2\sigma_{VM}}{3S_1}\right)^a \exp\left[b \cdot \left(\dfrac{J_1}{S_s} - 1\right)\right]$ $S_s = \sqrt{\sigma_1{}^2 + \sigma_2{}^2 + \sigma_3{}^2}, \ (S_1 = \sigma_1 - J_1/3), \ (J_1 = \sigma_1 + \sigma_2 + \sigma_3)$

Task 4: Global optimization software

Input:
- Model name
- Stress function-type
- Initial Guess constants

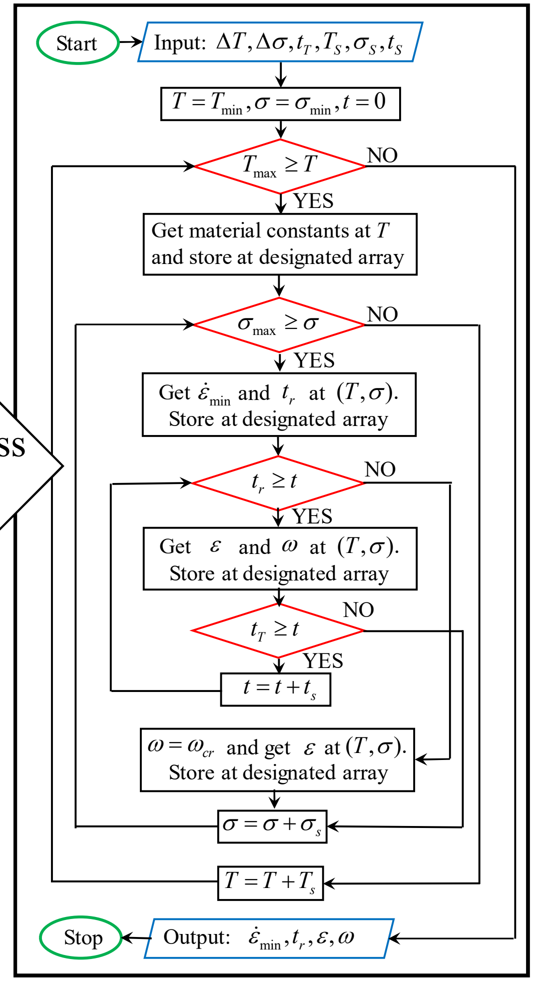
Assessment:
- NMSE (Normalized Mean Squared Error)
- Inflection point
- Physical realism

$\Big\}$ Human interaction

Output:
- Calibrated material constant.
- Stress parameter function.
- Most suitable model.

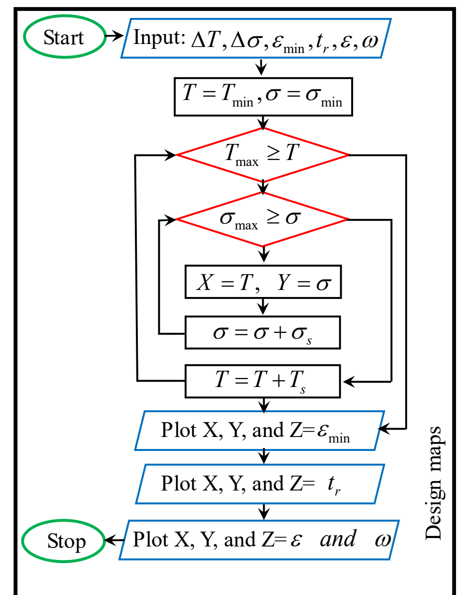
MATLAB process flow chart

Other group are in Excel function form. Requires higher human involvement.



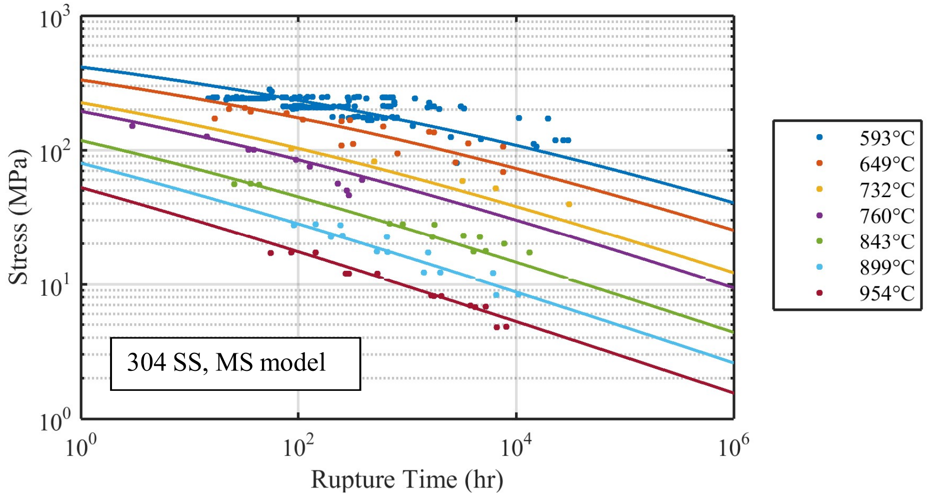
Step 1: Perform extrapolation

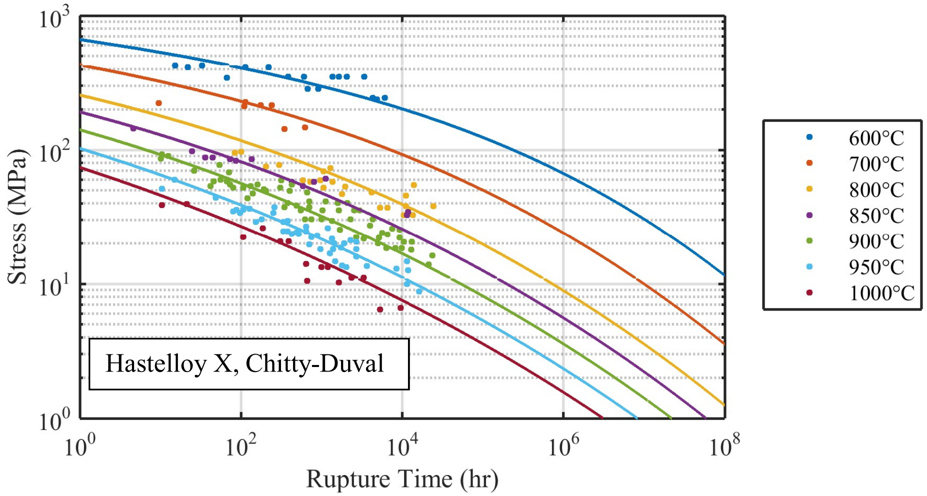
Temperature-range = $\Delta T = T_{max} - T_{min}$
Stress-range = $\Delta\sigma = \sigma_{max} - \sigma_{min}$
Target time = t_T
Rupture time = $t_r = f(T,\sigma)$
Temperature, Stress, and time step = T_s, σ_s, t_s
Current Temperature, Stress and time = T, σ, t
Minimum strain rate = $\dot{\varepsilon}_{min} = f(T,\sigma)$
Material constants = $f(T)$
Damage = ω, Critical damage = ω_{cr}
Strain = ε
X, Y = X and Y-coordinate array

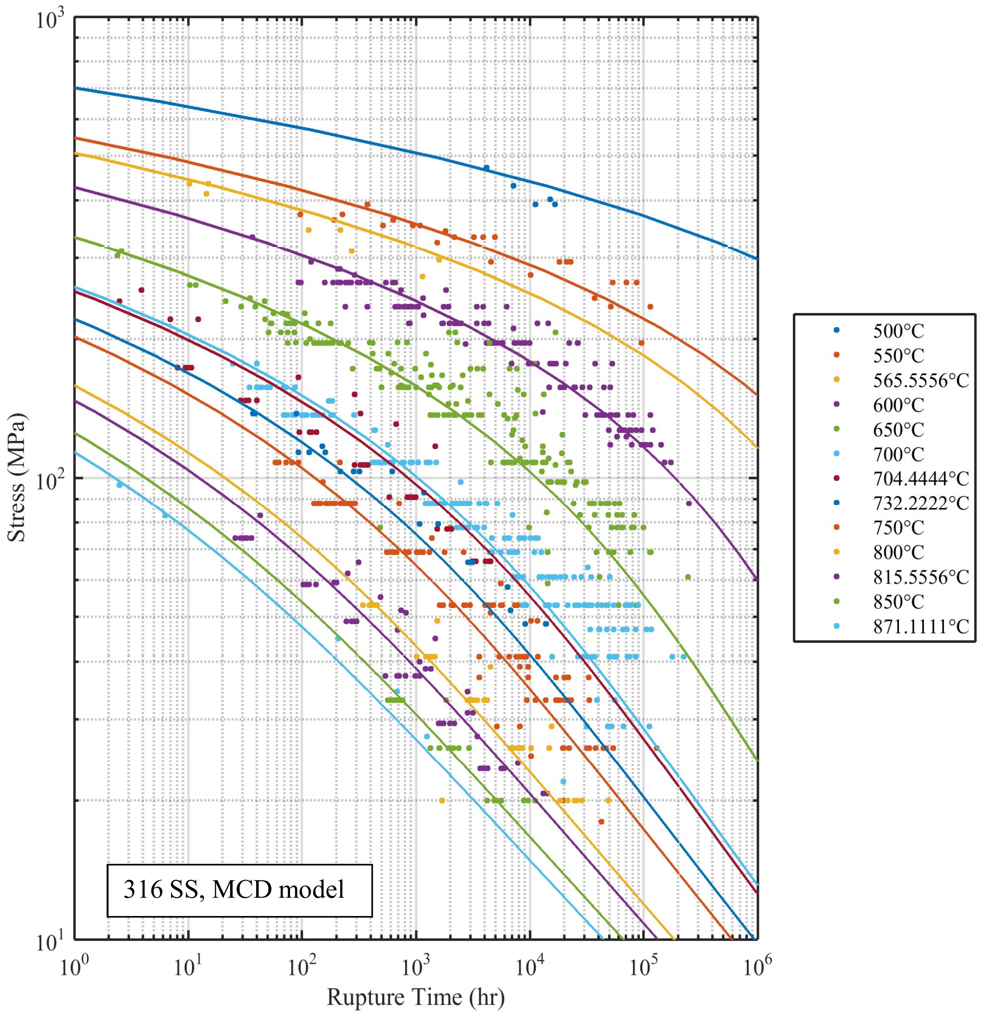


Step 2: Plot design maps

Analytic fit (Stress-rupture)







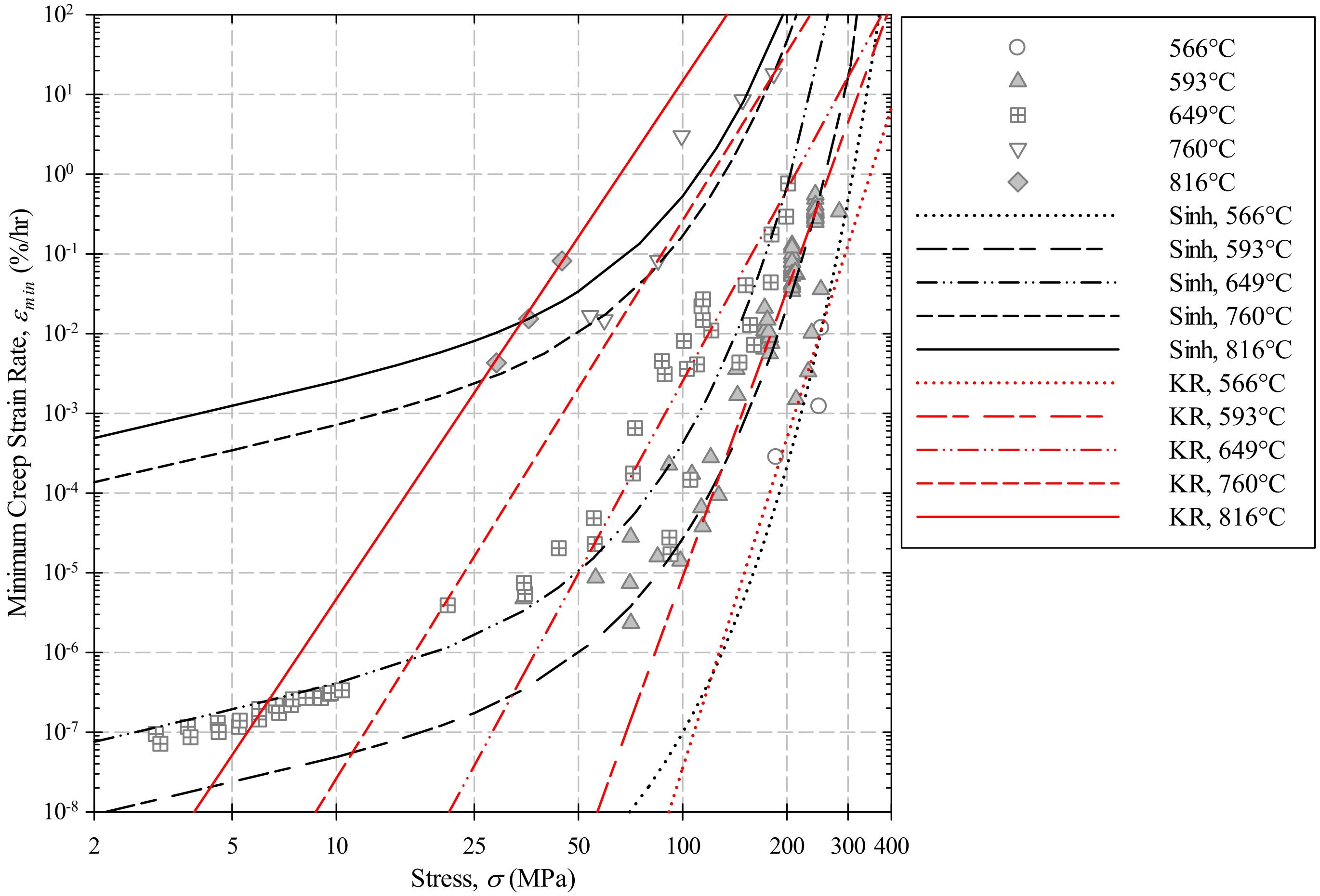
Minimum Creep Strain Rate

Norton Power Law (KR) $\dot{\varepsilon}_{\min} = A\sigma^n$

McVetty (Sinh) $\dot{\varepsilon}_c = B\sinh\left(\sigma/\sigma_s\right)$

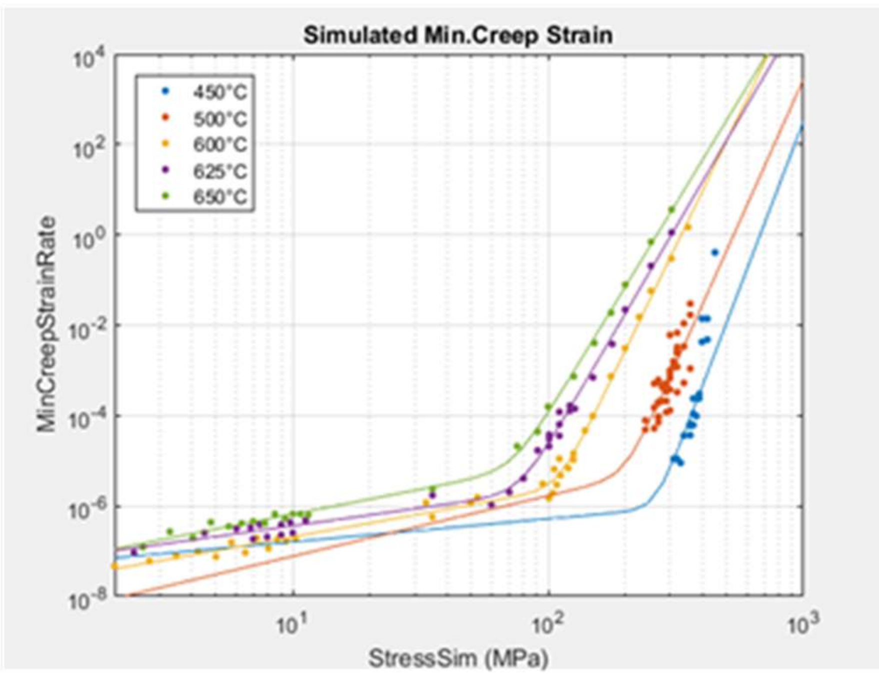
KR limitations: The KR minimum creep strain rate predictions are linear on a log-log scale and thus are not able to accurately model the sigmoidal behavior observed in the experimental data.

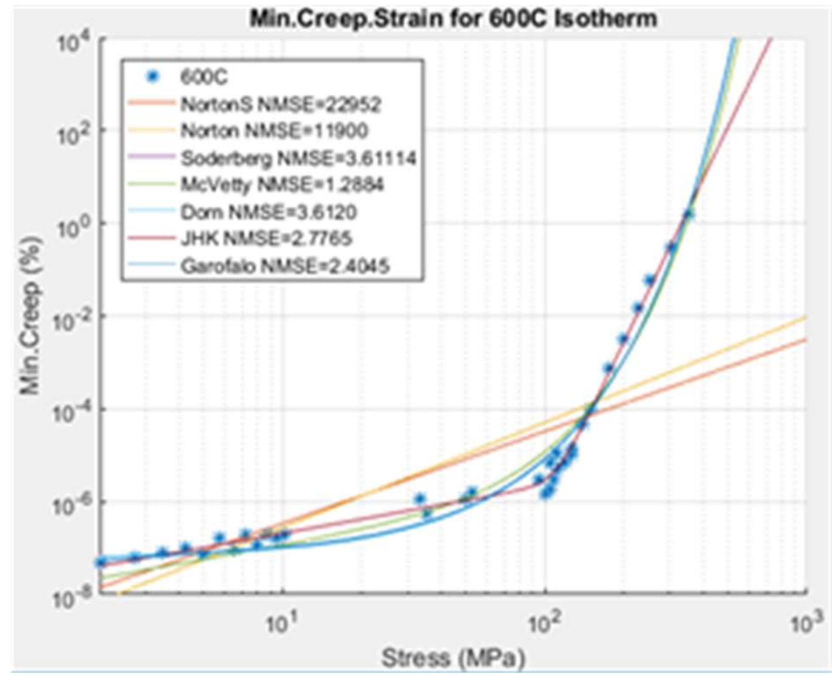
Sinh advantage: The Sinh minimum creep strain rate predictions bend on a log-log scale and are able to accurately model the sigmoidal behavior.



Comparison of Norton and McVetty model against 304 SS data

Minimum Creep Strain Rate





Comparison of various data model against P91 data

Creep deformation

Theta Projection (tertiary strain rate)

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

$$\dot{\varepsilon}_t = \theta_3\theta_4 \exp(\theta_4 t)$$

Omega Model

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \exp(\varepsilon\Omega)$$

$$\omega = \frac{t}{t_r} = \frac{\dot{\varepsilon}\Omega t}{1+\dot{\varepsilon}\Omega t}$$

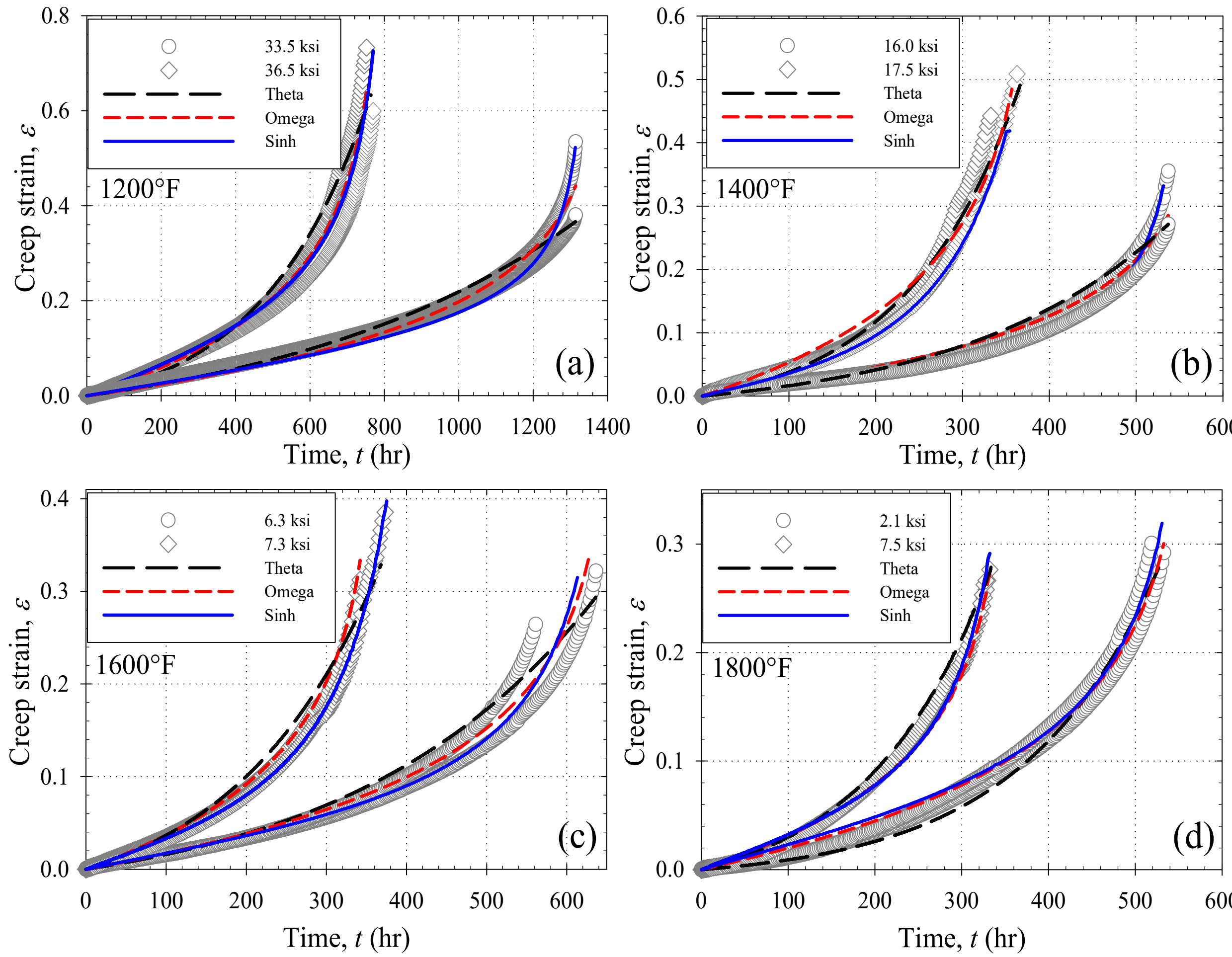
Sin-Hyperbolic Model

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

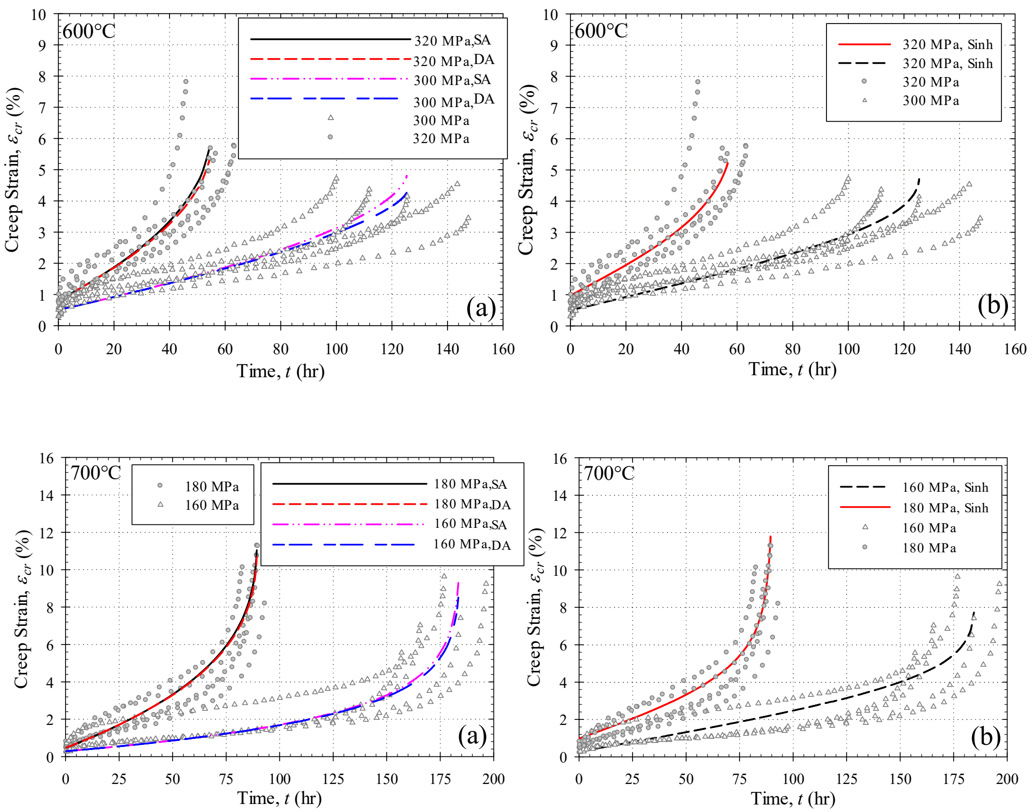
$$\dot{\omega} = \frac{M\left[1-\exp\left(-\phi\right)\right]}{\phi}\sinh\left(\frac{\sigma}{\sigma_t}\right)^{\chi}\exp\left(\phi\omega\right)$$

Ref: [4]

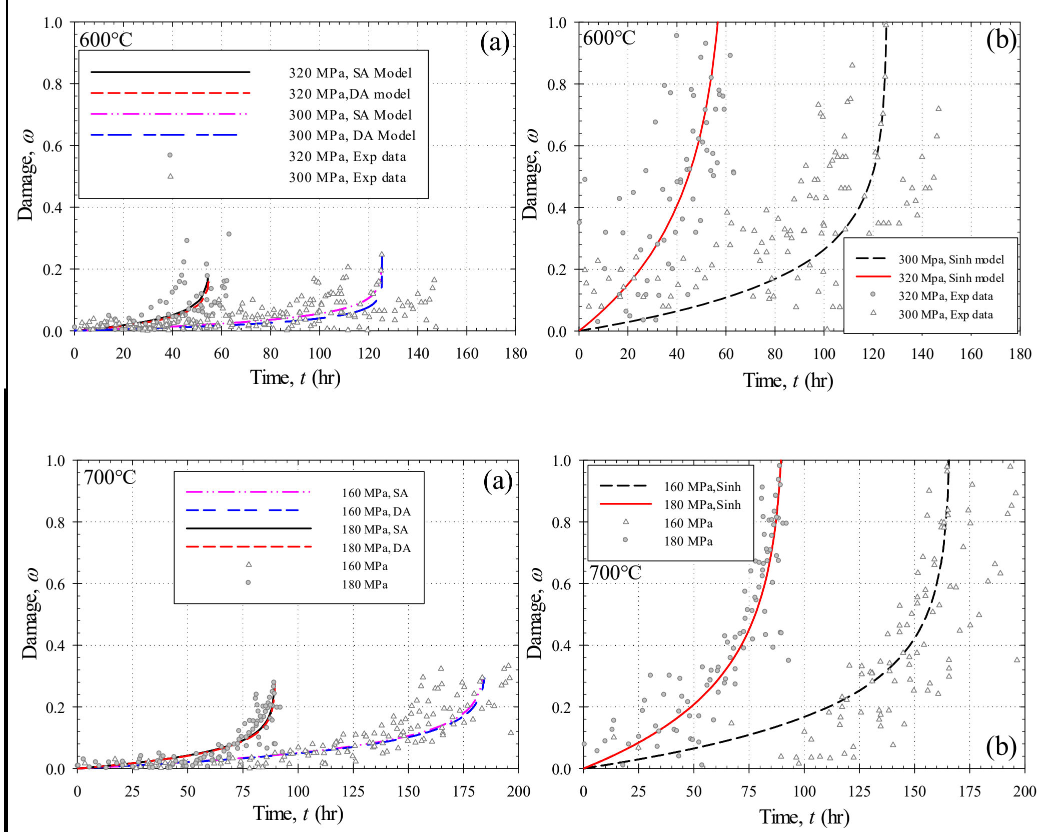
Comparison of Theta, Omega, and Sinh model against **Hastelloy X** creep data



CDM model fit

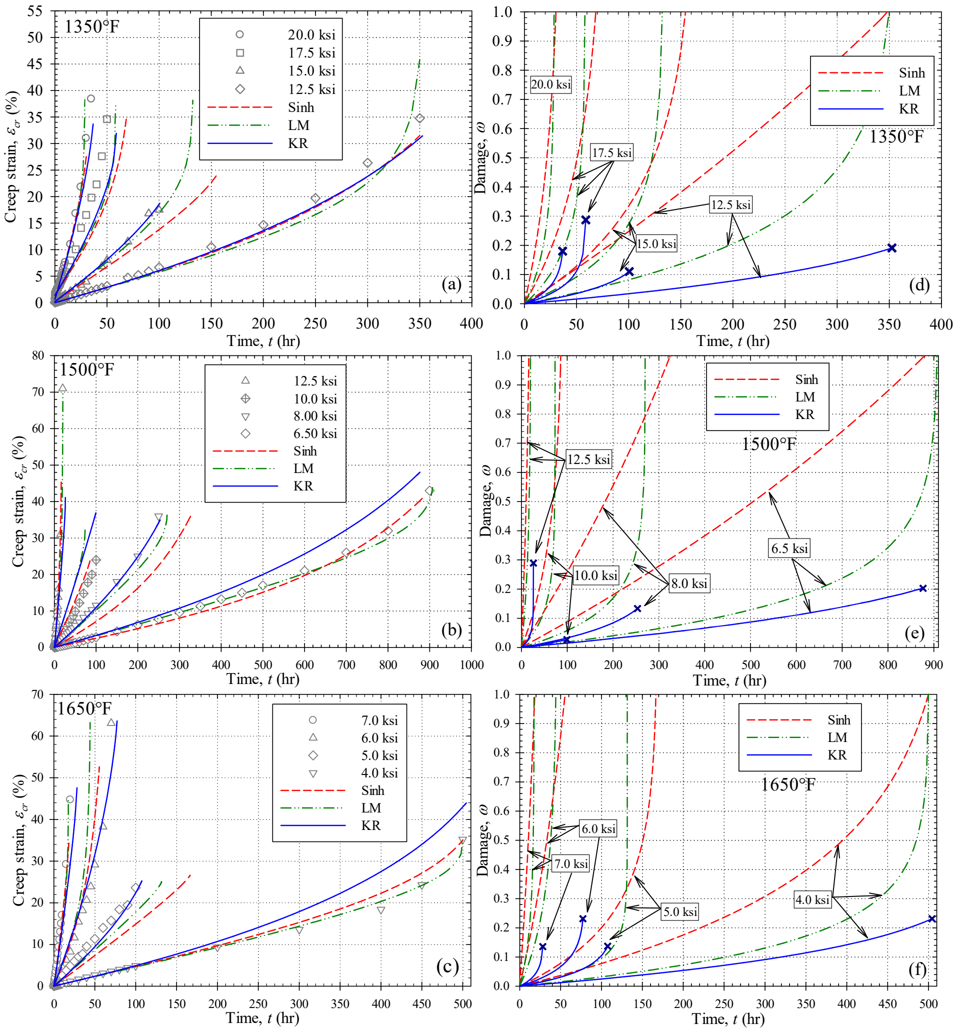


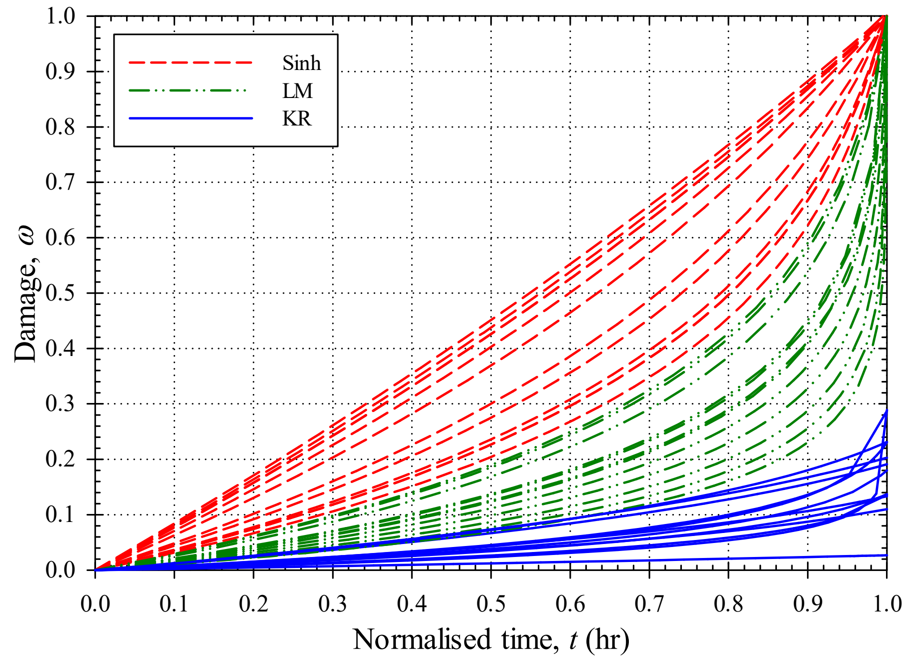
Comparison of Sinh and KR model against 304 SS creep strain data



Comparison of Sinh and KR model damage evolution against 304 SS analytic damage

CDM model fit





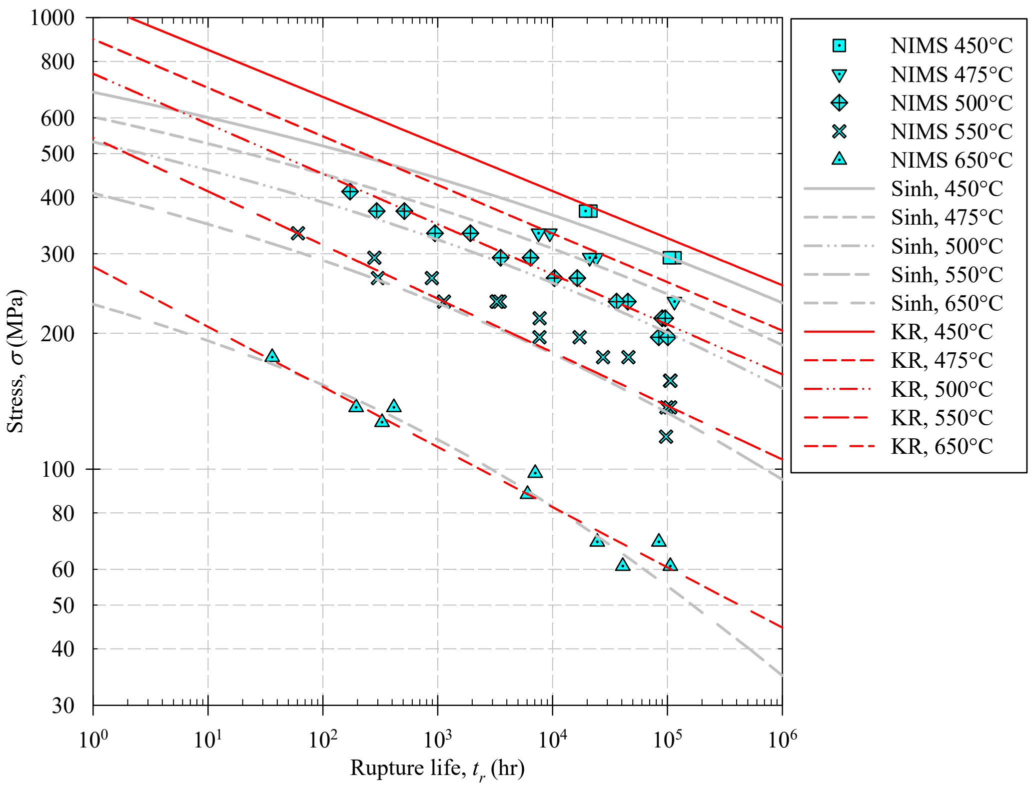
Comparison of Sinh, LM and KR model against 316 SS creep strain data

[1] Haque, M. S., and Stewart, C. M. (2015). Comparison of a New Sin-Hyperbolic Creep Damage Constitutive Model With the Classic Kachanov-Rabotnov Model Using Theoretical and Numerical Analysis. In *TMS 2015 144th Annual Meeting & Exhibition* (pp. 937-945). Springer, Cham.

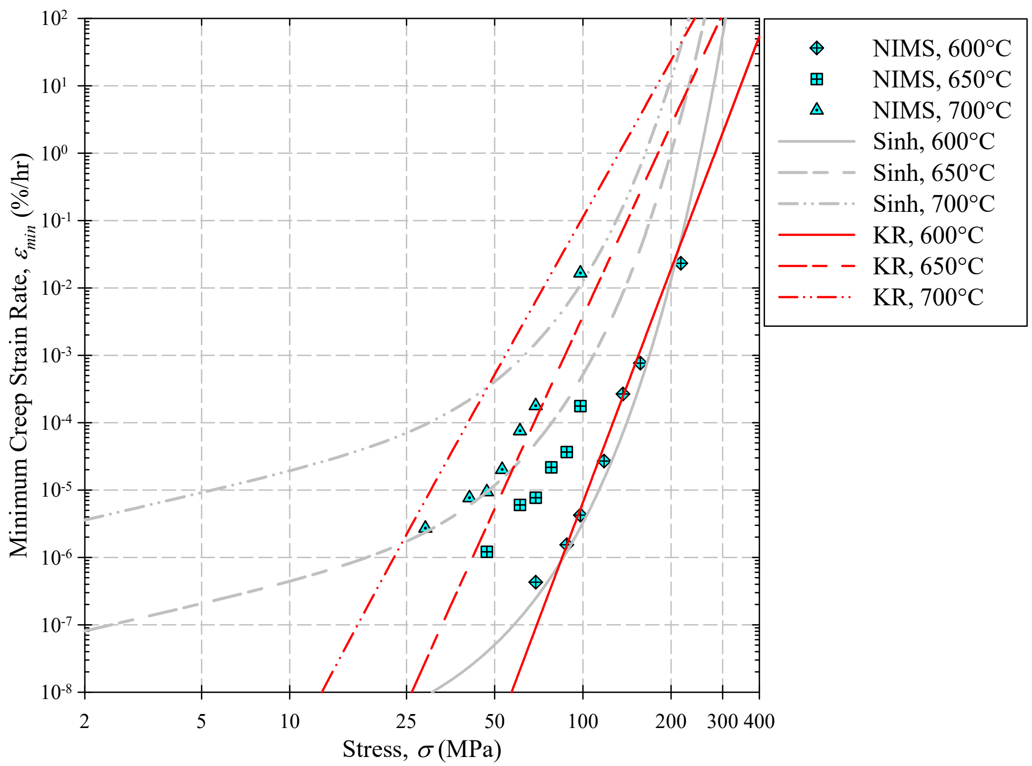
[14] Haque, M. S., and Stewart, C. M. (2017). Metamodeling of the Kachanov-Rabotnov, Liu-Murakami, and Sin-Hyperbolic Continuum Damage Mechanics based Creep Models. (**40% complete**)

Task 5: Post-Audit Verification

Post-audit validation with additional data that is not used in calibration



Stress-Rupture

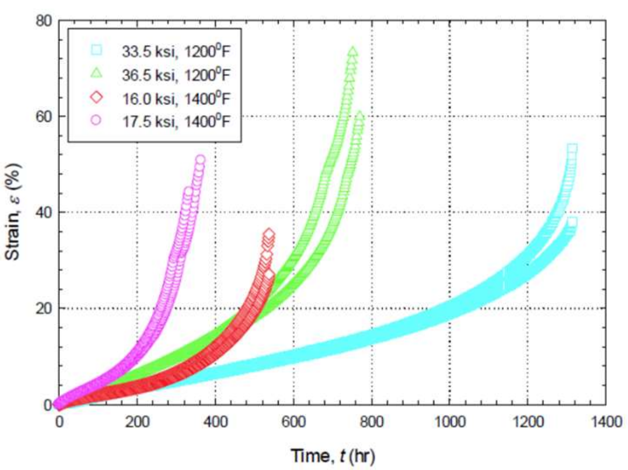


Minimum-creep-strain-rate

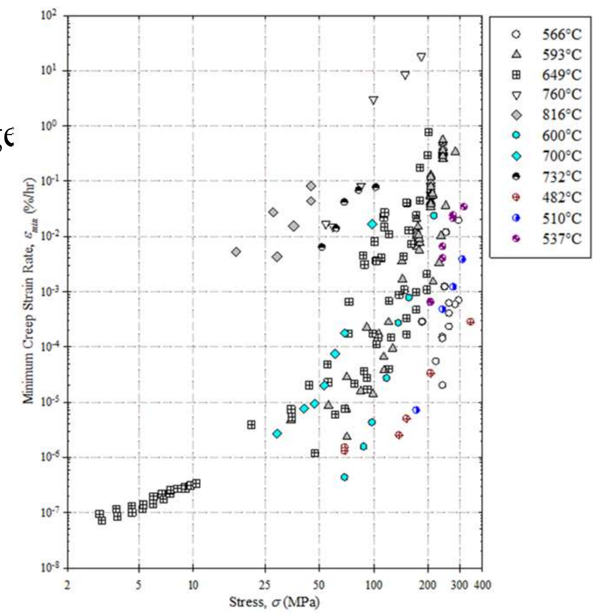
Task 6: Disparate Data problem

Gap exist in creep data. → Data is not available in the regime or form of interest. → Creep deformation extrapolation using short-term data may lead to unreliable prediction. → Cross-calibration to any and every form of data can improve extrapolation.

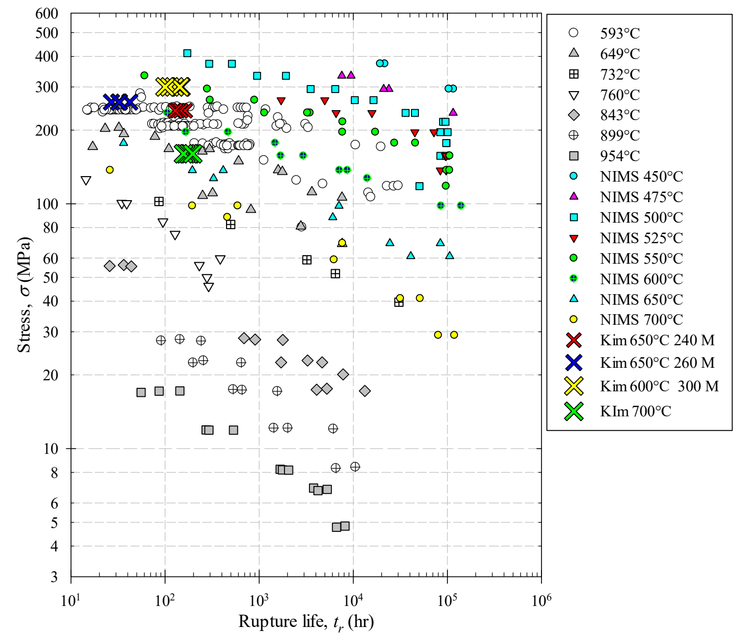
Data exists in diaspora
Unreliable extrapolation
Limited up to certain multiple of the longe



Creep deformation



Minimum-creep-strain-rate

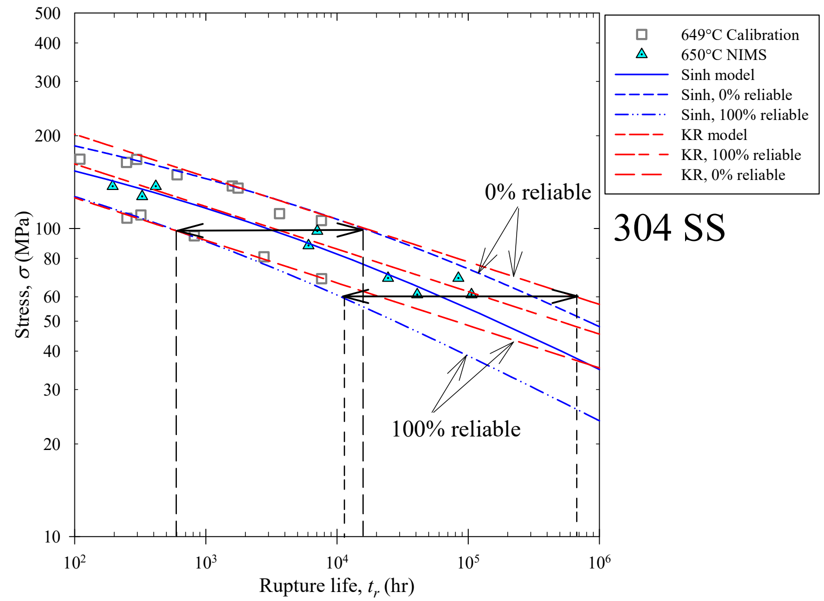


Stress-Rupture

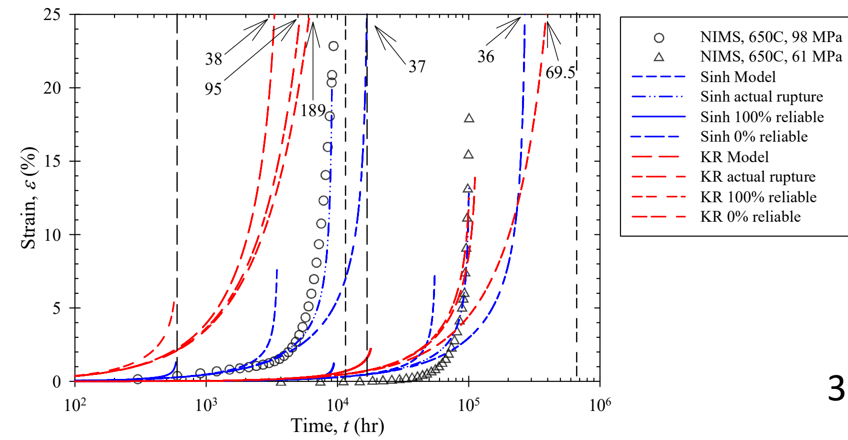
Disparate Data problem: Improved Extrapolation

Calibration procedure for CDM models to disparate creep data

Model Selection	Select the creep model of interest. (Kachanov-Rabotnov, Sinh, etc.)
Segregation	Segregate the model into equations related to each type of creep data. (Minimum-Creep-Strain-Rate, Stress-Rupture, Creep Deformation, etc.)
Calibration	Calibrate the material constants of the equations using the creep data.
Regression	Use regression analysis to convert material constants into temperature-dependent functions. $f_i(T)$
Validation	Take the pre-calibrated model and compare it to additional data not used in the calibration process.
Design	Make interpolative and extrapolative prediction of creep behavior. Plot these predictions as Creep Design Maps.



304 SS



Development of a Design Map

- Tensile properties
- The variable of interest
- Design envelope

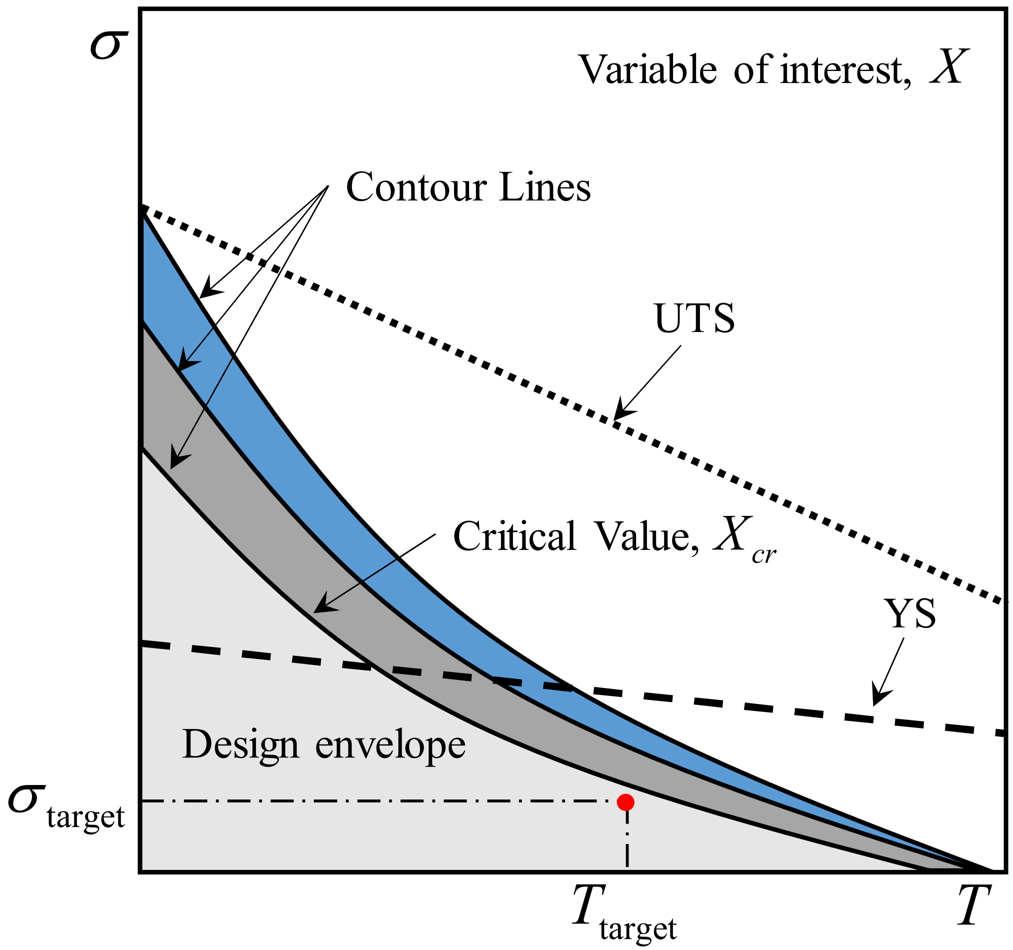
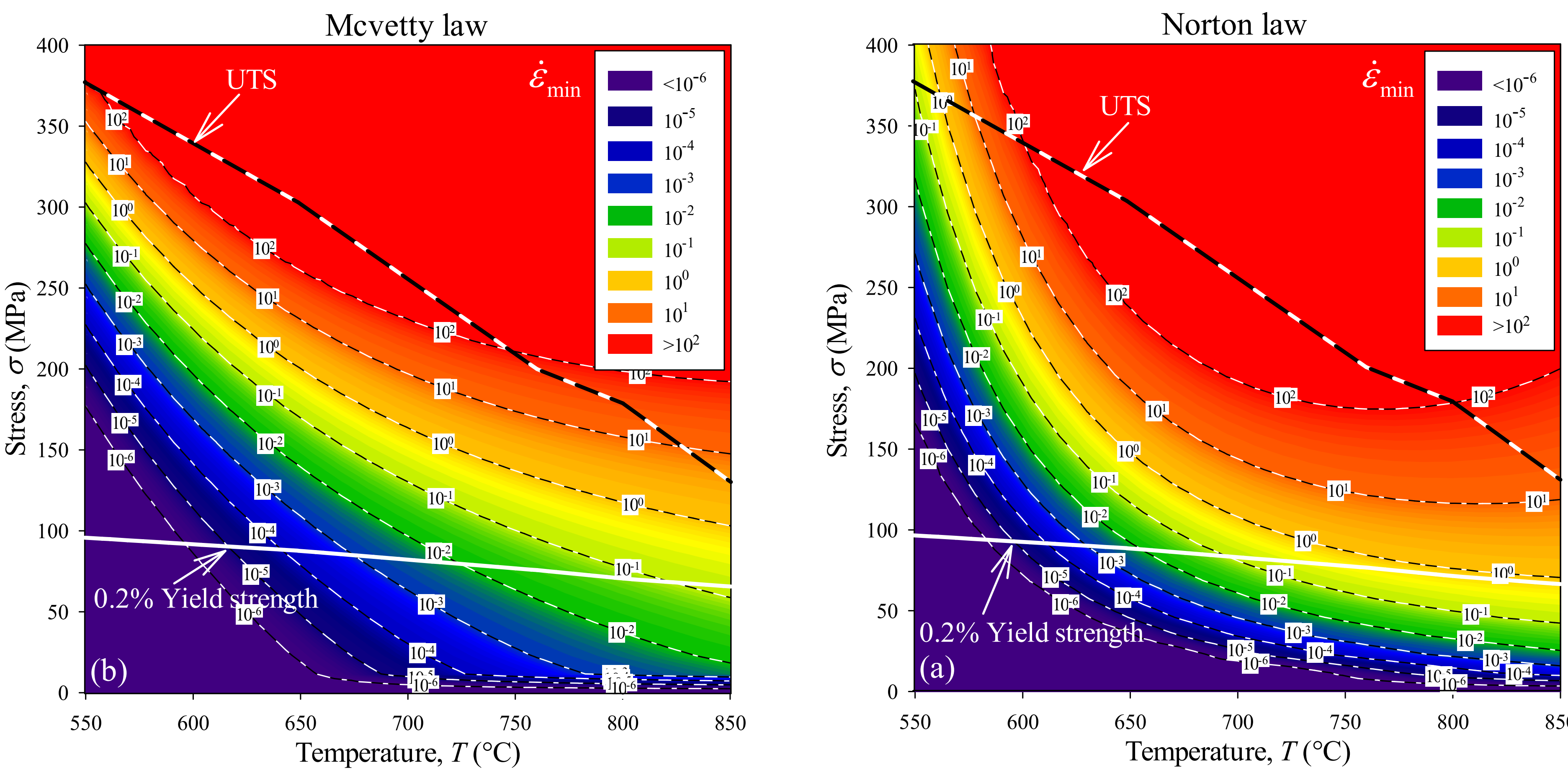


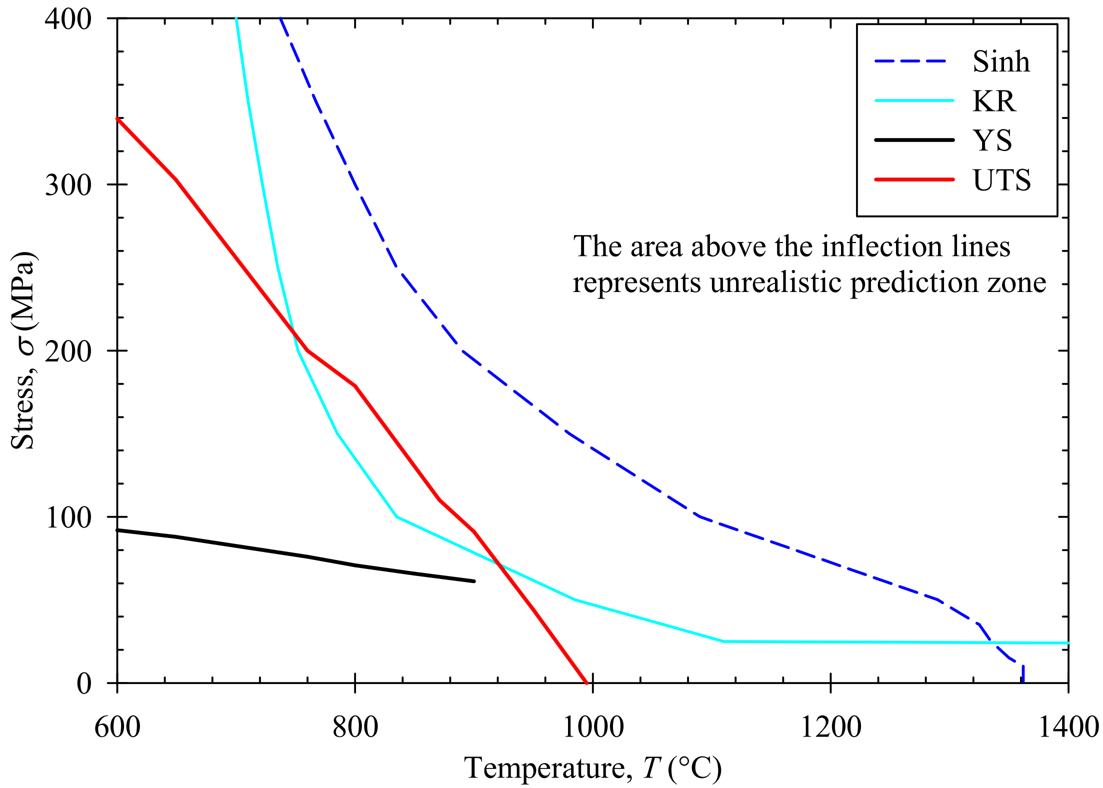
Illustration of design map

Extrapolation and Interpolation: Design Maps



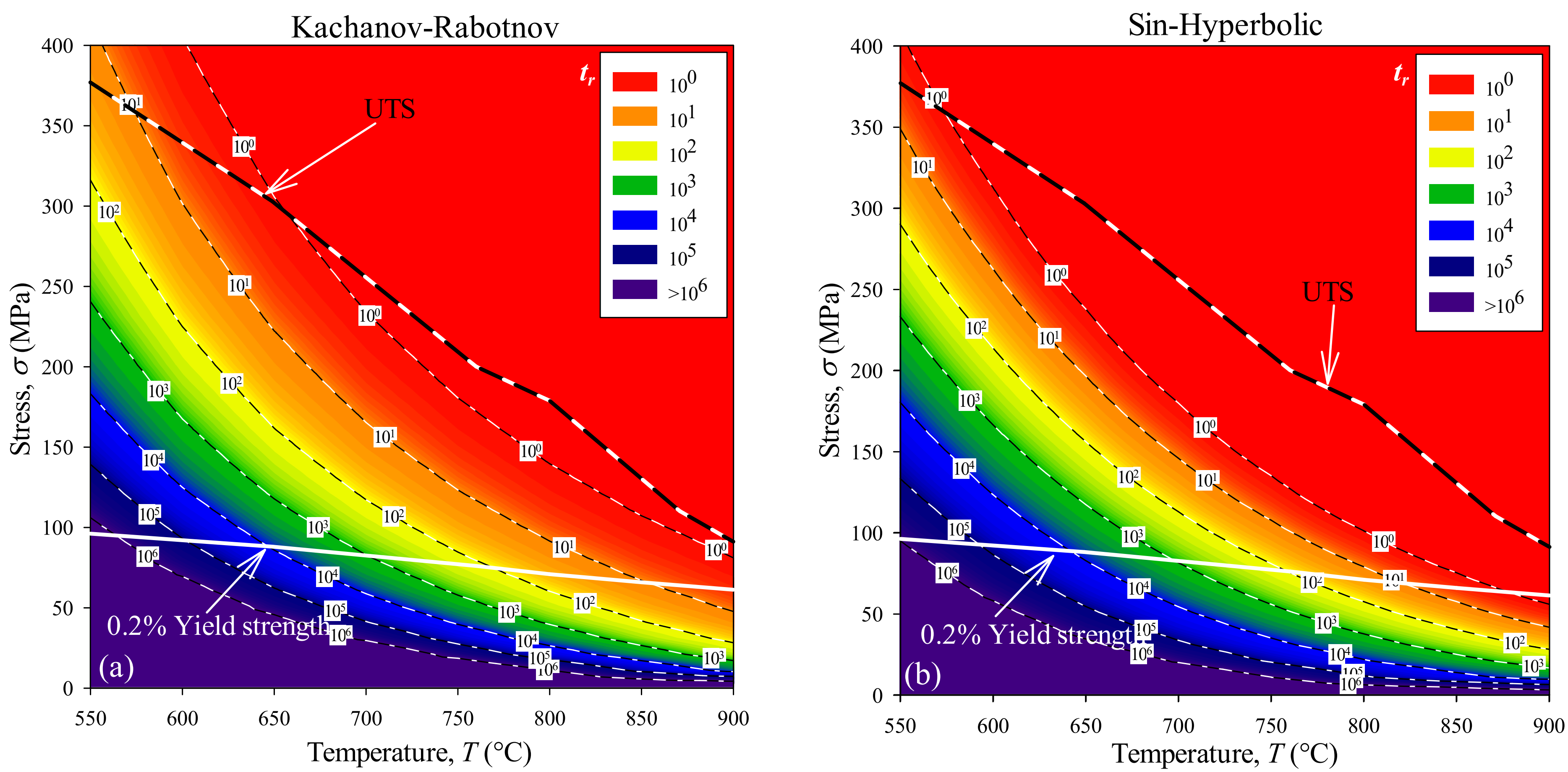
Minimum-creep-strain-rate design maps

Extrapolation and Interpolation: Design Maps



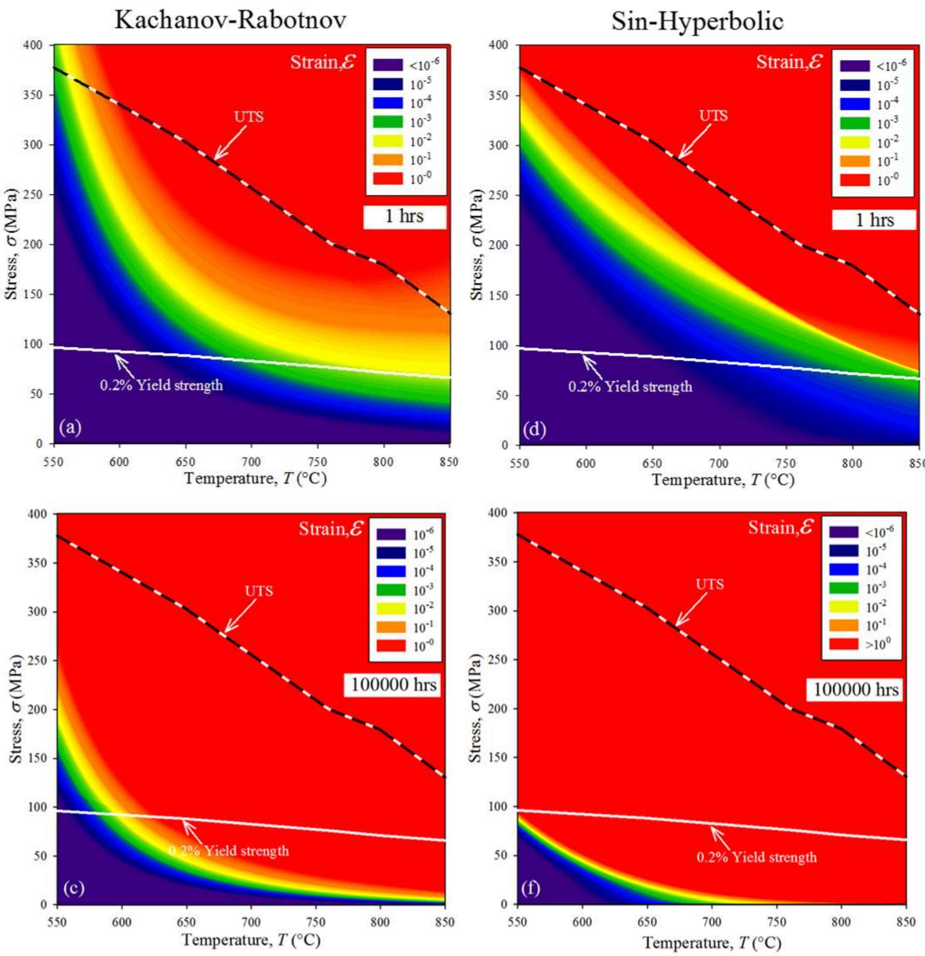
Minimum-creep-strain-rate Inflection

Design Maps

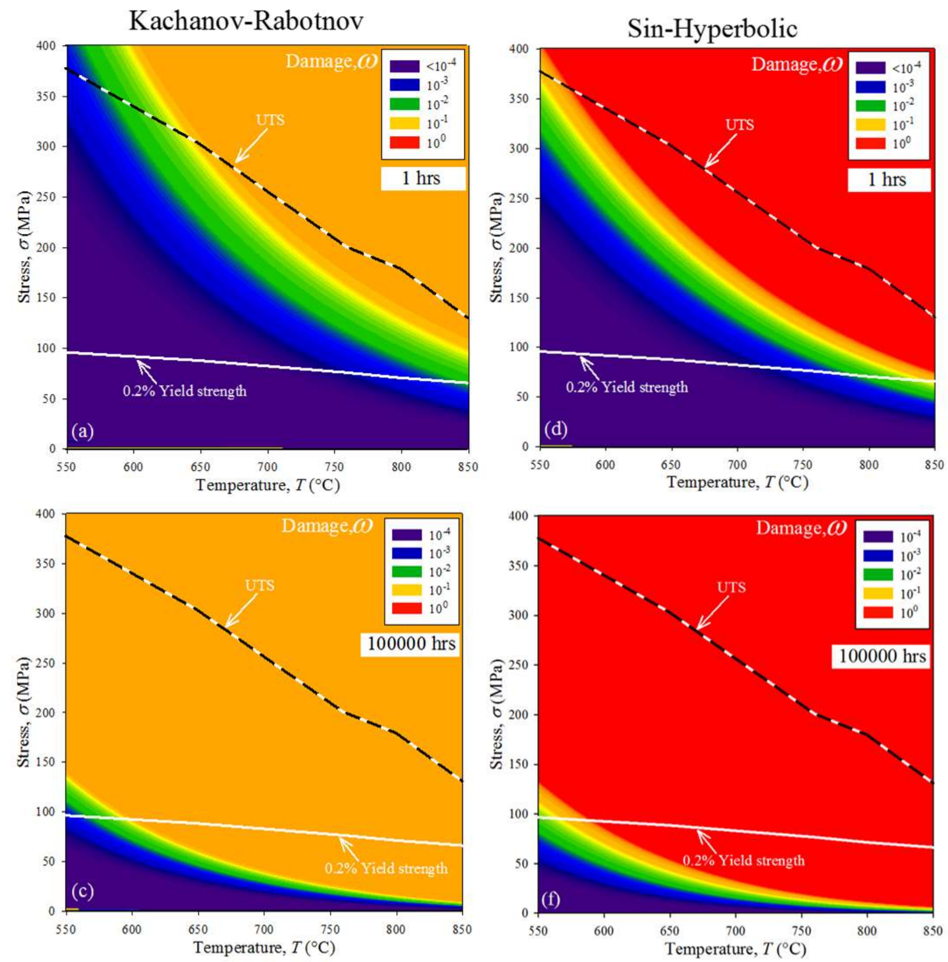


Stress-Rupture design maps

Design Maps



Deformation design maps



Damage design maps

Task 7: Metamodeling: Finding the “best ” model

A “**metamodel**” can be described as a combinational model, derived from rearranging, modifying, and/or expanding the functional relationships between different models.

Stress-Rupture

- **Eight** commonly used TTP models
- **Four** newly developed model

Creep-deformation

- Omega model
- Theta Projection
- Sin-hyperbolic model

Continuum Damage Mechanics

- Kachanov-Rabotnov
- Sin-hyperbolic
- Liu-Murakami

- A detail explanation of stress-rupture metamodeling will be presented.
- Summary and progress of the other metamodeling group is reported.

Metamodeling: Stress-Rupture

- **Metamodel:**

$$P_{HS} = \frac{\log(t_r) - \alpha_0 - \alpha_1 T^r}{(T^r - \alpha_2{}^r)^q}$$

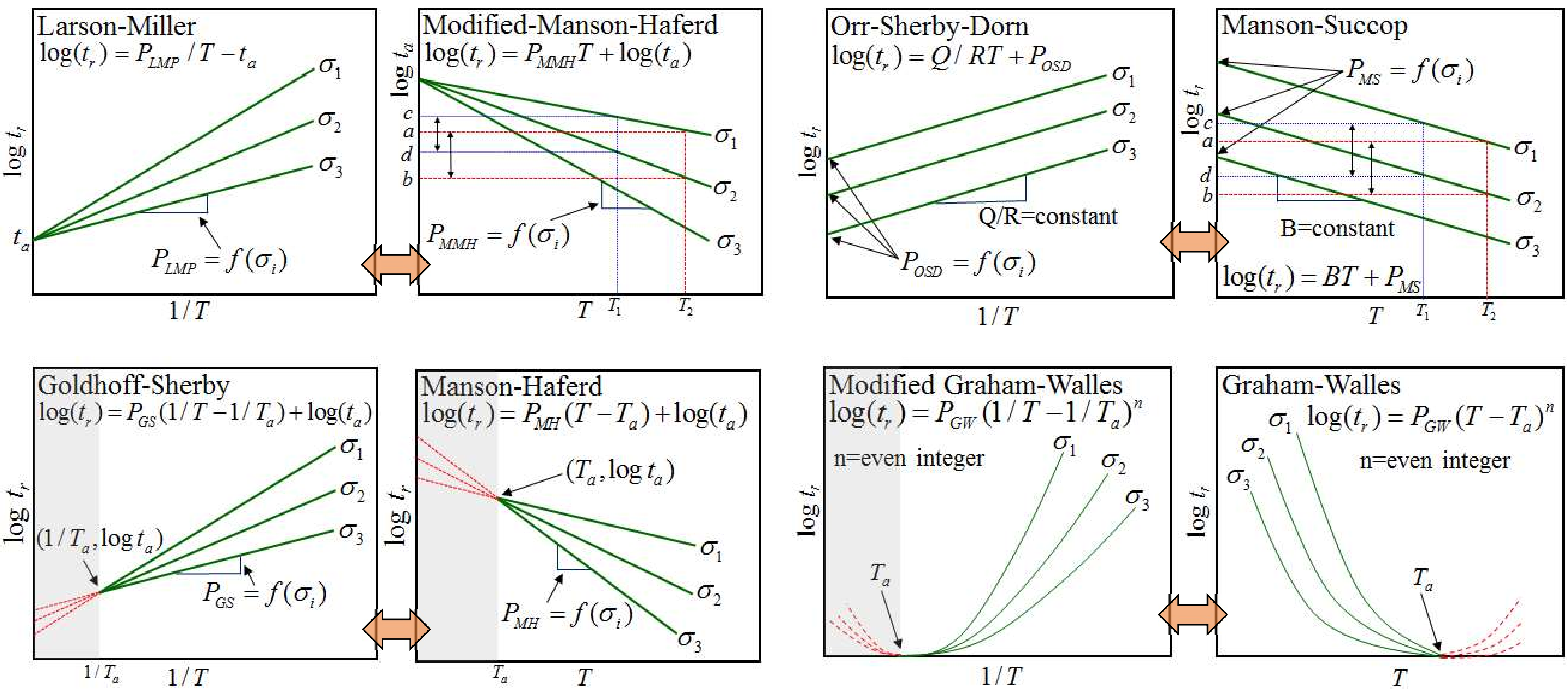
- **Parent model**: Larson-Miller

$$P_{LMP} = T(\log(t_r) + t_a)$$

New models

$P_{unified} = \frac{\log(t_r) - \alpha_0 - \alpha_1 T^r}{(T^r - \alpha_2{}^r)^q}$							
Model	Year	Parametric equation	Iso-stress equation	Material constants	Characteristics	Metamodel condition	Ref.
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	$\alpha_2 = \alpha_1 = 0$ $r = -1, q = 1$	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	$\alpha_2 = \alpha_1 = 0$, $r = 1, q = 1$	--
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	$r = -1, q = n$, $\alpha_1 = 0$	--

Mirror Models



Mirror Models (Cont.)

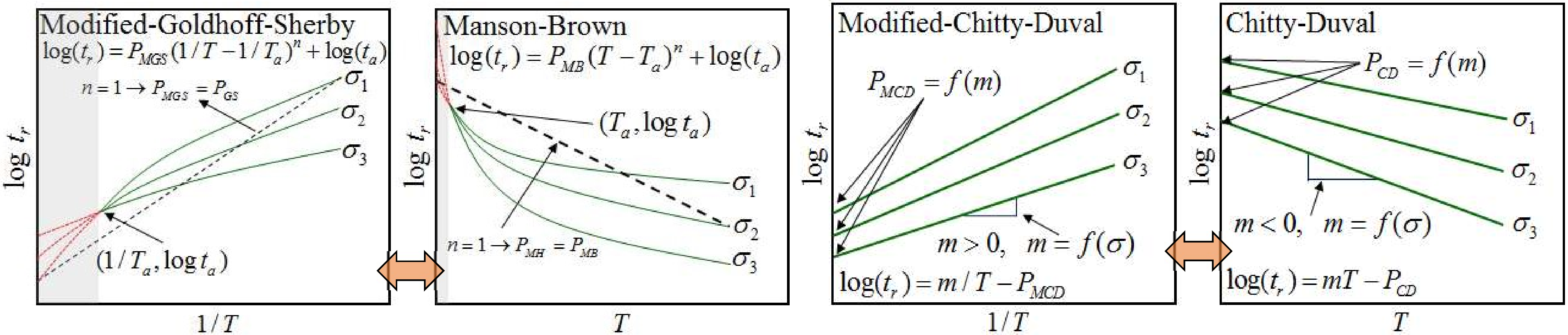
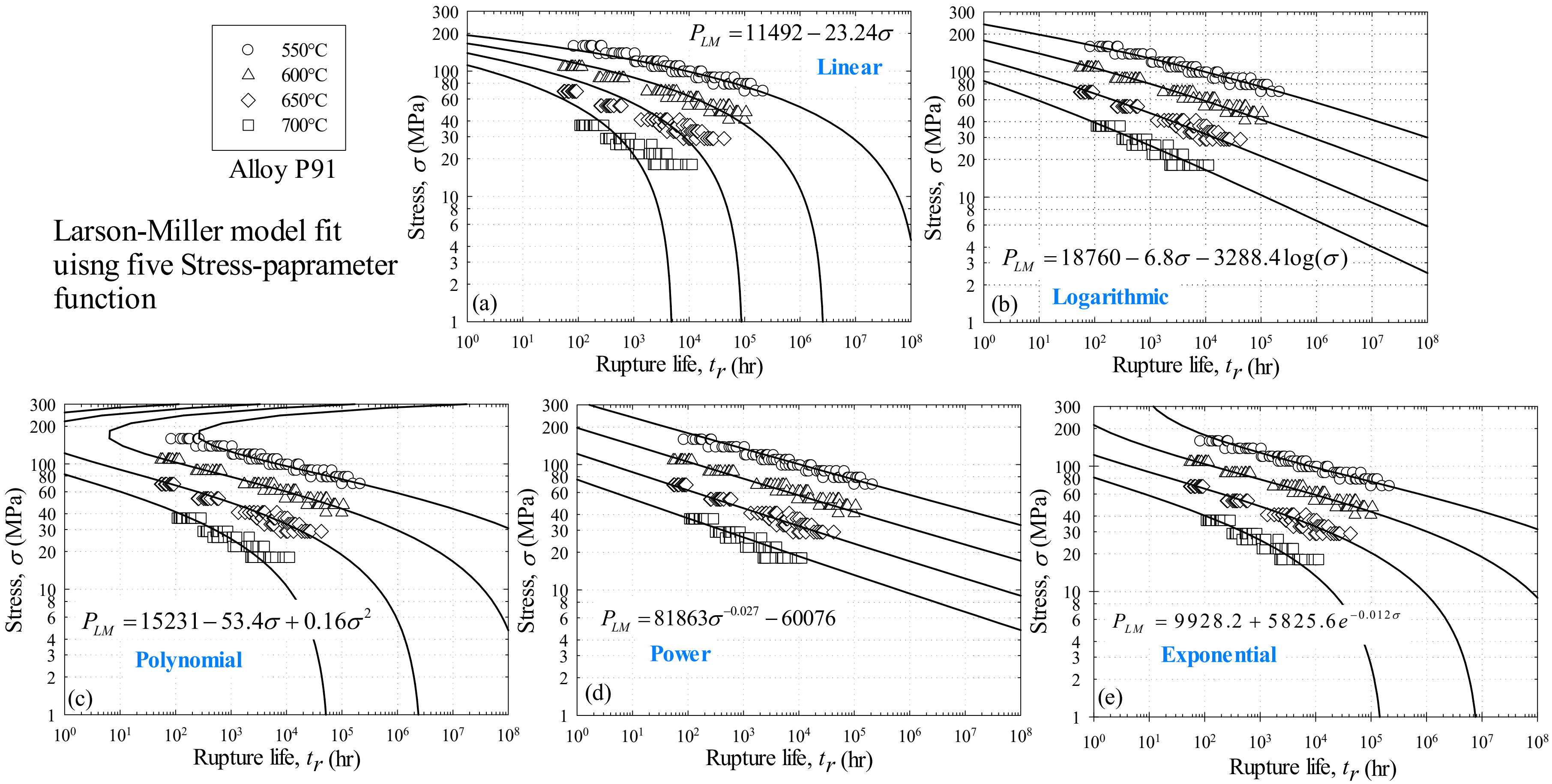


Table – List of the "mirror pairs" that have similar mathematical form whose isostress lines are inverse/mirror image due to the temperature variable T being inverted

(1)	Larson-Miller	↔	Mod-Manson-Haferd
(2)	Goldhoff-Sherby	↔	Manson-Haferd
(3)	Mo-Goldhoff-Sherby	↔	Manson-Brown
(4)	Orr-Sherby-Dorn	↔	Manson-Succop
(5)	Mod-Graham-Walles	↔	Graham-Walles
(6)	Mod-Chitty-Duval	↔	Chitty-Duval

Stress-parameter function

- The **stress-parameter function** is a mathematical expression of the master curve such that a temperature invariant parameter can be obtained for a given stress.



Stress-parameter function

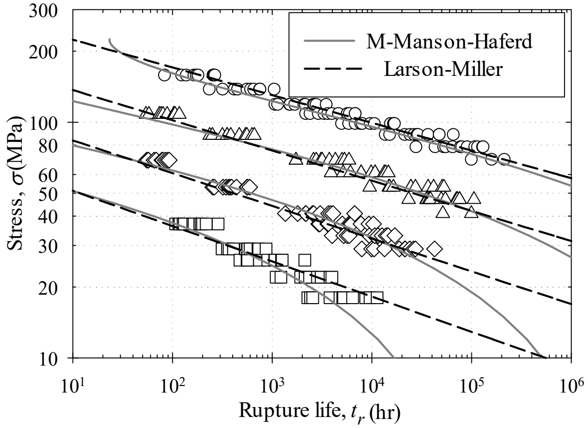
Table – Effect of typical stress-parameter functions during extrapolation on Larson-Miller

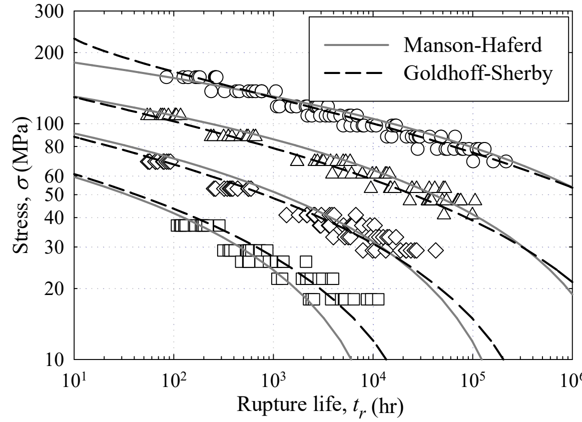
Function type	Equation	Prediction type	Inflection? $\frac{dP_i}{d\sigma}=0$
Linear	$a+b\sigma$	High Weakening	**NO**
Logarithm	$a+b\sigma+c\log(\sigma)$	Stable	**NO**
Ploy-nominal	$a+b\sigma+c\sigma^2$	Weakening	**YES**
Power	$a+b\sigma^c$	Stable	**NO**
Exponential	$a+be^{c\sigma}$	Weakening	**YES**

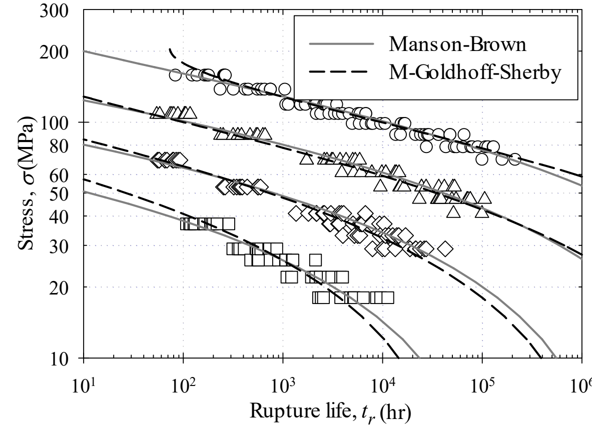
- Force fit to a particular function may lead to poor prediction.
- A flexible option to choose function may improve prediction accuracy.

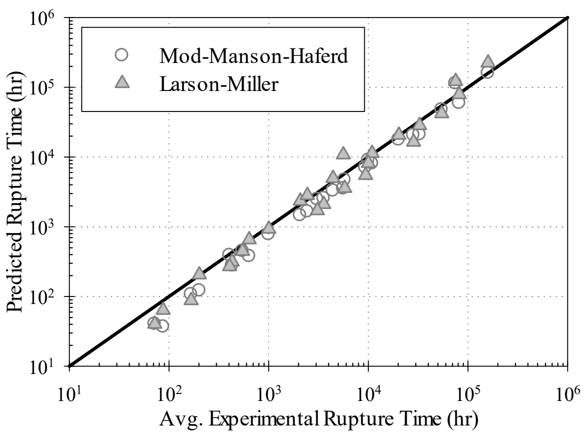
Model fit to alloy P91 data

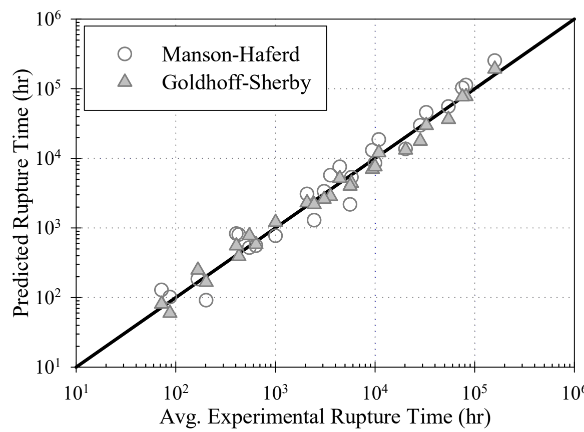
○ 550°C
△ 600°C
◇ 650°C
□ 700°C

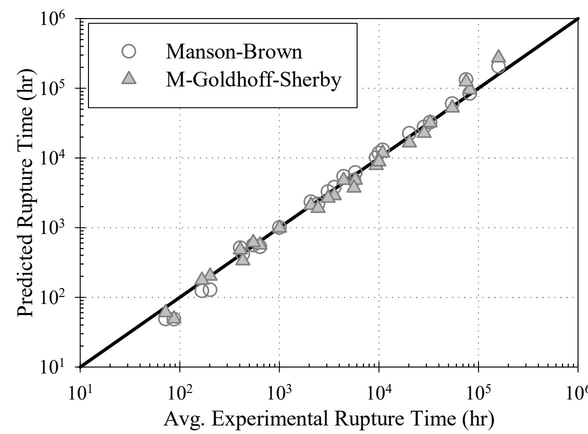




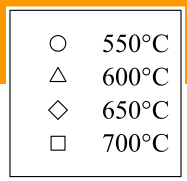


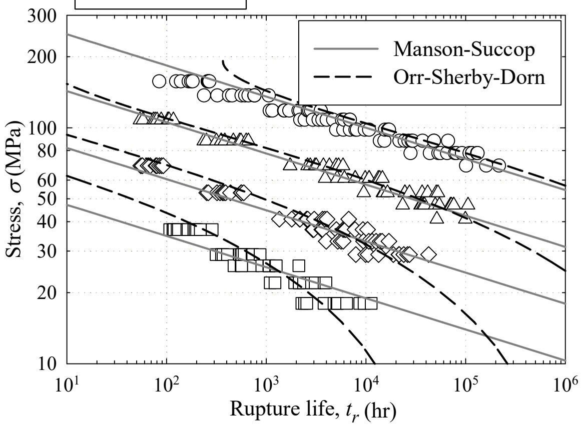


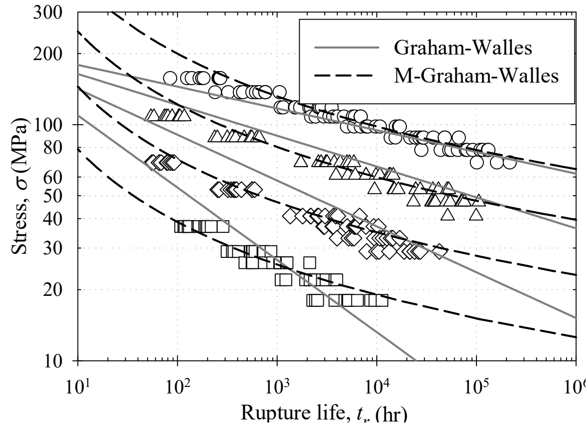


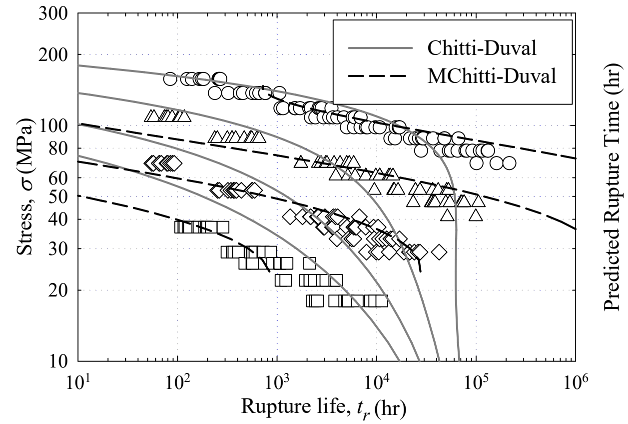


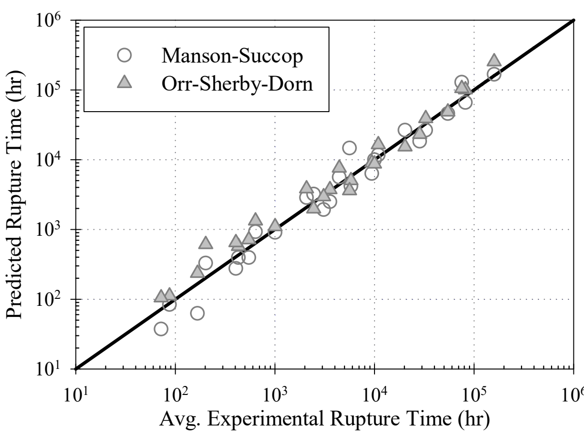
Model fit to alloy P91 data

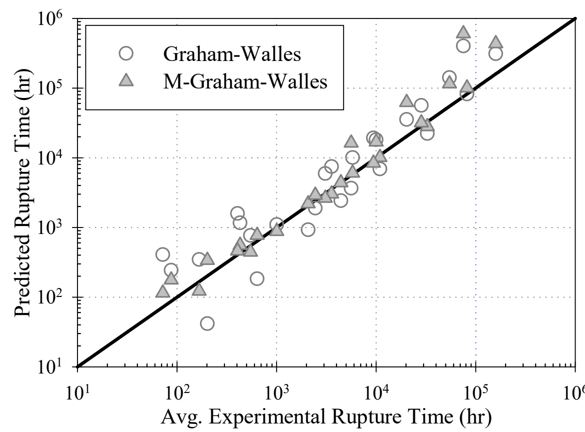


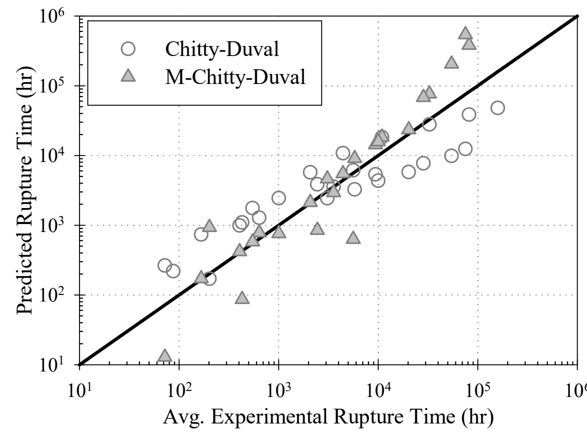












Calibrated Material constants and Stress-Parameter functions

- For most model, polynomial function produce the best goodness-of-fit.
- Polynomial function may exhibit inflection during extrapolation.
- Logarithmic and power function does not exhibit inflection during extrapolation.
- Inflection may be avoided by selecting next good-fit function at the cost of accuracy.

Table – Material constants, stress-parameter functions, inflection status, and overall NMSE of the models

Model	Material constants	Master curve/Stress-parameter function $P_i = f(\sigma)$ with maximum R^2	Max. R^2	Inflection status	Overall NMSE
MMH	$\alpha_0 = 25.0$	$P_{MMH} = 2.9E-7\sigma^2 - 1.2E-4\sigma - 0.03$	0.97	YES	2.46
LM	$\alpha_0 = -19.0$	$P_{LM} = 22000 - 4680\log(\sigma)$	0.98	NO	3.16
MH	$\alpha_0 = 16.6$, $\alpha_2 = 210$	$P_{MH} = -1E-4\sigma - 0.025$	0.98	NO	6.05
GS	$\alpha_0 = 32.0$, $\alpha_2 = 248$	$P_{GS} = -.05\sigma^2 + 27.1\sigma + 10435$	0.98	YES	1.60
MB	$\alpha_0 = 14.0$, $\alpha_2 = 25.0$	$P_{MB} = 3E-10\sigma^2 - 2E-7\sigma - 2E-5$	0.99	NO	1.49
MGS	$\alpha_0 = 520$, $\alpha_2 = 12.4$	$P_{MGS} = 0.31\sigma^2 - 12.8\sigma - 82076$	0.99	YES	1.70
MS	$\alpha_1 = -0.036$ $\alpha_2 = 5.00$	$P_{MS} = -3.29\ln(\sigma) + 39.22$	0.98	NO	5.49
OSD	$\alpha_1 = 12100$ $\alpha_2 = 5.00$	$P_{MB} = 2E-4\sigma^2 - 7E-2\sigma - 2E-12.48$	0.99	YES	8.69
GW	$\alpha_2 = 1005$	$P_{GW} = 5E-8\ln(\sigma) - 3E-7$	0.94	NO	66.8
MGW	$\alpha_2 = 900$	$P_{MGW} = 7E8\sigma^{-0.975}$	0.98	NO	64.6
CD	$\alpha_1 = f(\sigma)$	$P_{CD} = -3E-4\sigma^2 + 0.2\sigma + 5.1$; $\alpha_1 = -5E-4\sigma^{0.9}$	0.99	YES	42.8
MCD	$\alpha_1 = f(\sigma)$	$P_{MCD} = -11.1\ln(\sigma) + 19.2$; $\alpha_1 = 1E4\log(\sigma) + 3$	0.99	YES	81.6

Normalized Mean Square Error

- Normalized Mean Square Error: $NMSE = \frac{1}{n}\sum_{i=1}^{n}[(X_{sim,i} - X_{\exp,i}) / X_{\exp,i}]^2$

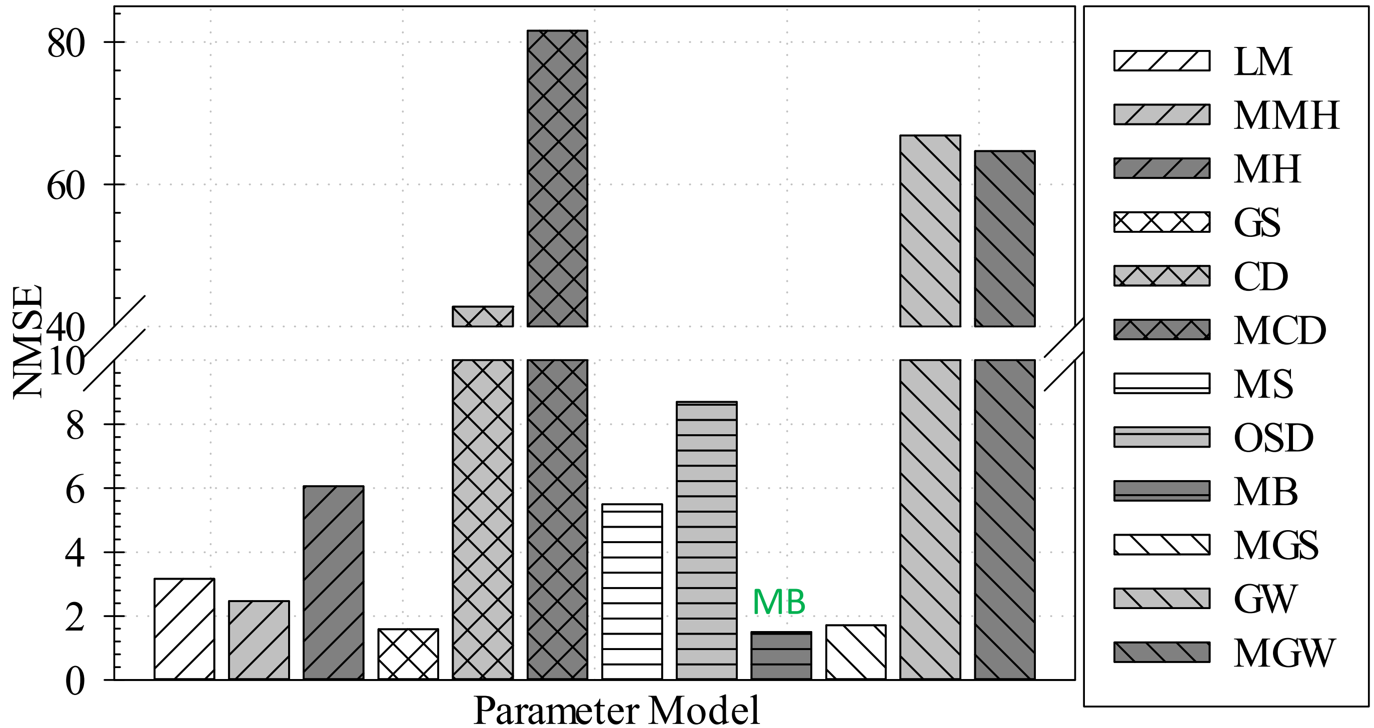


Figure - Comparison of the cumulative creep rupture NMSE of the models

- The Manson-Brown and Goldhoff Sherby produces the lowest NMSE.

Guideline to model selection

- ASME (American Society of Mechanical Engineers)
- ECCC (European Creep Collaborative Committee)
- ASTM (American Society for Testing and Materials)

Data pre-processing	• Inclusion of ongoing data • Exclusion of outlier data • Removal of low stress data
Procedure	• Follow Metamodeling procedure
The purpose of modeling	• Interpolation • Extrapolation
Temperature feasibility	• Point of convergence
Stress feasibility	• Inflection point stress
Material behavior	• Strengthening • Weakening • Stable behavior
Post-processing	• Check physical realism • Goodness-of-fit

Creep Deformation Metamodel

Table 6 – Combinational model summary

No	Base model	Creep Strain Rate	Damage	Life Prediction
			Theta-Omega Identity, $I_{\theta\Omega}=\left(\dot{\varepsilon}_0/\theta_3\theta_4\right)$	
M1	Theta	$\dot{\varepsilon}=(\dot{\varepsilon}_0/I_{\theta\Omega})\exp\left(\theta_4 t\right)$	$\omega(t)=\dfrac{t}{t_r}$	$t_r=\dfrac{1}{\theta_4}\ln\left(\dfrac{\varepsilon_r\theta_4 I_{\theta\Omega}}{\dot{\varepsilon}_0}+1\right)$
M2	Omega	$\dot{\varepsilon}=I_{\theta\Omega}\theta_3\theta_4\exp\left(\Omega\varepsilon\right)$	$\omega(t)=\dfrac{t}{t_r}$	$t_r=\left(\dfrac{1}{I_{\theta\Omega}\theta_3\theta_4\Omega}\right)$
			Omega-Sinh Identity, $I_{\Omega S}=\dot{\varepsilon}_0/A\sinh\left(\sigma/\sigma_s\right)$	
M3	Omega	$\dot{\varepsilon}=I_{\Omega S}A\sinh(\sigma/\sigma_s)\exp(\Omega\varepsilon)$	$\omega(t)=\dfrac{t}{t_r}$	$t_r=\left(\dfrac{1}{I_{\Omega S}A\sinh(\sigma/\sigma_s)\Omega}\right)$
M4	Sinh	$\dot{\varepsilon}=(\dot{\varepsilon}_0/I_{\Omega S})\exp\left(\lambda\omega^{3/2}\right)$	$\omega(t)=-\dfrac{1}{\phi}\ln\left[1-\left[1-\exp(-\phi)\right]\dfrac{t}{t_r}\right]$	$t_r=\left(\dfrac{1}{\dot{\varepsilon}_0\cdot\Omega}\right)$
			Sinh-Theta Identity, $I_{S\theta}=\theta_3\theta_4/A\sinh(\sigma/\sigma_s)$	
M5	Sinh	$\dot{\varepsilon}=(\theta_3\theta_4/I_{S\theta})\exp\left(\lambda\omega^{3/2}\right)$	$\omega(t)=-\dfrac{1}{\phi}\ln\left[1-\left[1-\exp(-\phi)\right]\dfrac{t}{t_r}\right]$	$t_r=\dfrac{1}{\theta_4}\ln\left(\dfrac{\varepsilon_r}{\theta_3}+1\right)$
M6	Theta	$\dot{\varepsilon}=I_{S\theta}A\sinh(\sigma/\sigma_s)\exp\left(\theta_4 t\right)$	$\omega(t)=\dfrac{t}{t_r}$	$t_r=\dfrac{1}{\theta_4}\ln\left(\dfrac{\varepsilon_r\theta_4}{I_{S\theta}A\sinh(\sigma/\sigma_s)}+1\right)$

CDM Metamodel

KR-LM metamodel
$I_{t_r,KR-LM} = \ln\left(\frac{M_K \sigma^{\chi} (\phi_K + 1)}{M_L \sigma^{q}}\right) - \ln\left(\frac{1-\exp(-\phi_L)}{\phi_L}\right) - \ln(\phi_K + 1)$ $\omega_L = (-\phi_K / \phi_L) \ln(1-\omega_K) + I_{t_r,KR-LM} / \phi_L$
LM-Sinh metamodel
$I_{t_r,LM-\mathrm{Sinh}} = \ln\left(\frac{M_L \sigma^{P}}{M_S \,\mathrm{Sinh}(\sigma / \sigma_t)}\right) - \ln\left(\frac{1-\exp(-\phi_S)}{\phi_S}\right) + \ln\left(\frac{1-\exp(-\phi_L)}{\phi_L}\right)$ $\omega_{\mathrm{S}} = (\phi_L / \phi_S)\omega_L + I_{t_r,LM-\mathrm{Sinh}} / \phi_S$
Sinh-KR metamodel
$I_{t_r,\mathrm{Sinh}-KR} = \ln\left(\frac{M_K \sigma^{\chi} (\phi_K + 1)}{M_S \,\mathrm{Sinh}(\sigma / \sigma_t)}\right) - \ln\left(\frac{1-\exp(-\phi_S)}{\phi_S}\right) - \ln(\phi_K + 1)$ $\omega_{\mathrm{S}} = (-\phi_K / \phi_S) \ln(1-\omega_K) + I_{t_r,\mathrm{Sinh}-KR} / \phi_S$

Creep Deformation Metamodeling process

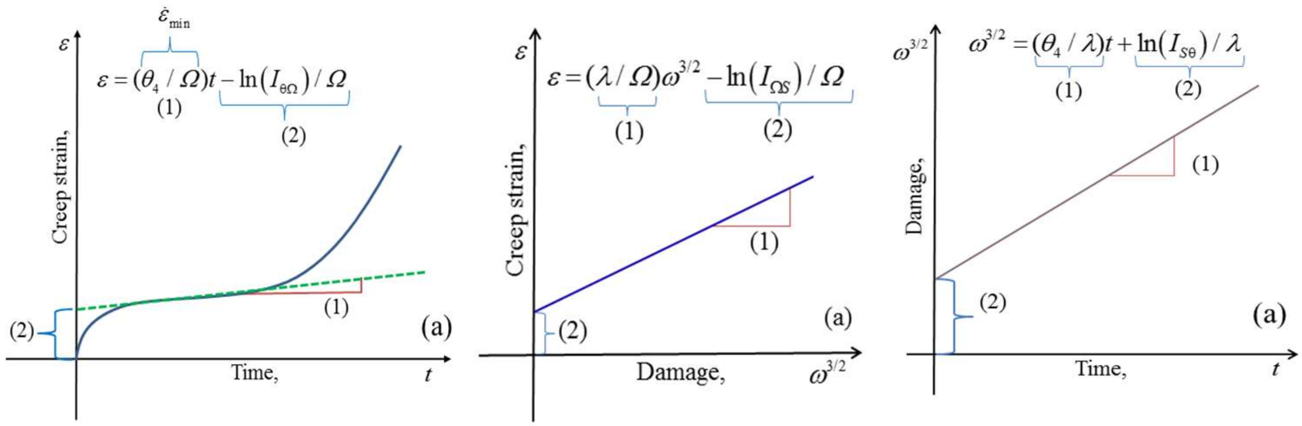
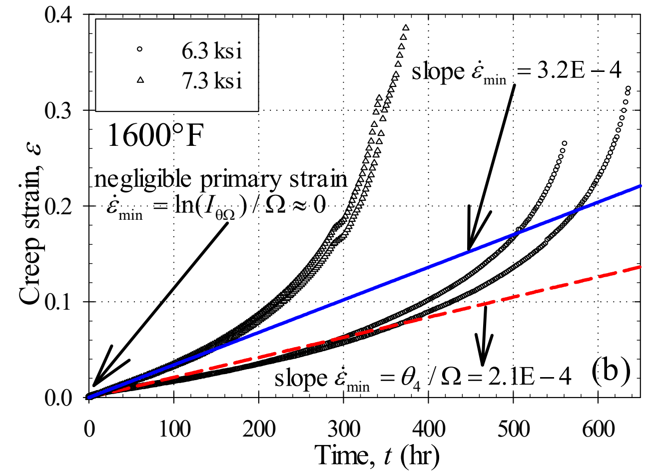
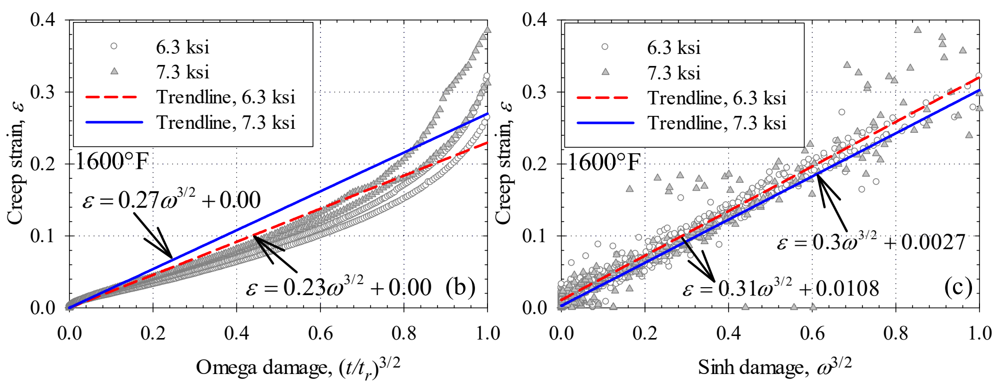


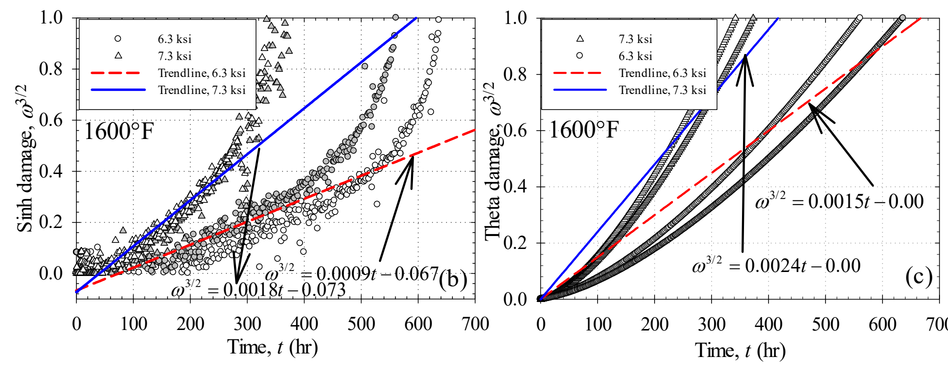
Figure: Graphical approach to model transformation (a) Theta-Omega, (b), Omega-Sinh and (c) Sinh-Theta



Theta-Omega



Omega-Sinh



Sinh-Theta

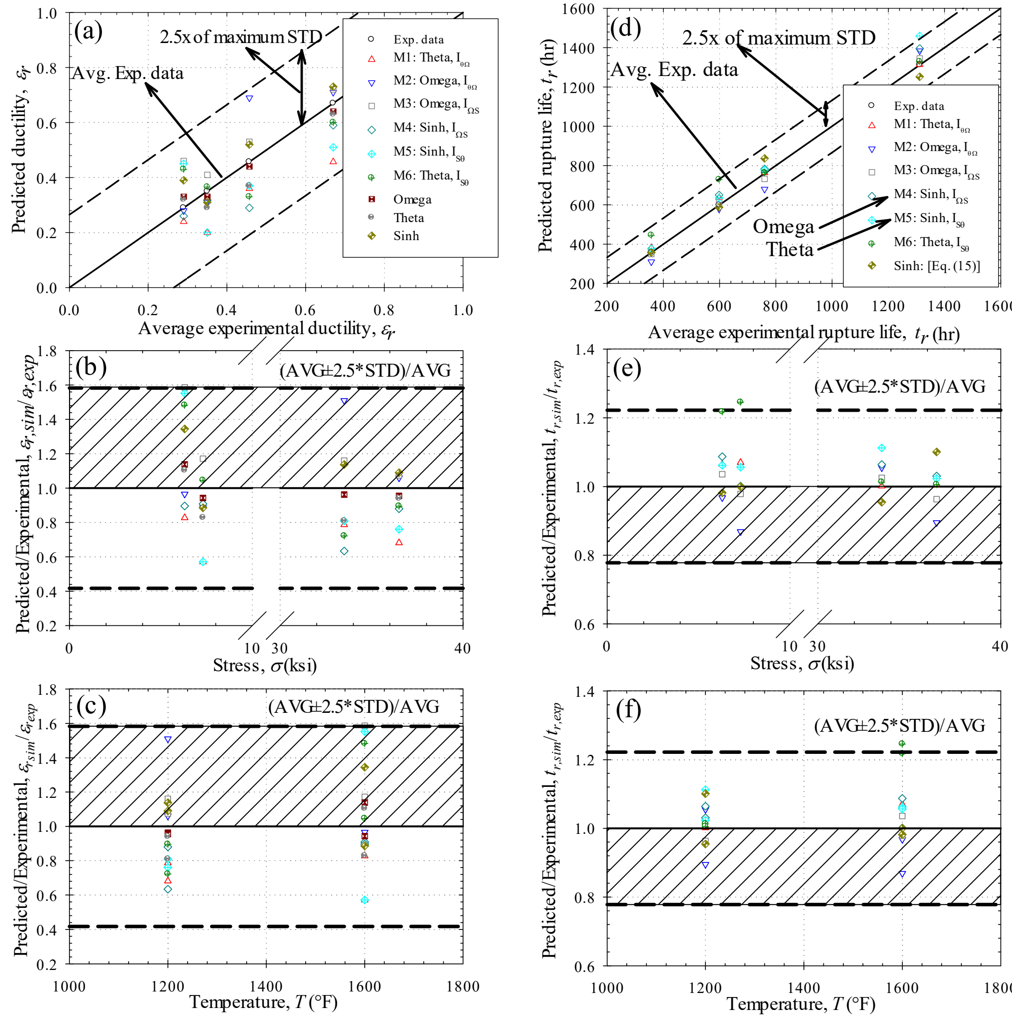
Assessment

- Normalized Mean Squared Error

$$NMSE = \frac{1}{n}\sum_{i=1}^{n}[(X_{sim,i} - X_{\exp,i}) / X_{\max}]^2$$

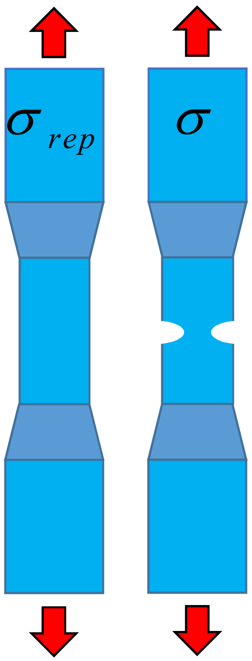
- Physical realism and numerical stability
- Conservatism

Figure: Model performance in predicting (a-c) creep ductility and (d-f) rupture life where the dotted lines indicate 2.5x of the maximum standard deviation in repeated tests. In the ratio plots, the dotted line indicates the ratio of 2.5x of the maximum standard deviation divided by the average obtained in repeated tests. The highlight areas indicate conservative predictions.



Task 8: Multiaxial Representative Stress Function

Representative stress *(σ_{rep})*
The stress applied to a plain bar that results in the same effective strain accumulation or rupture life as that obtained in a notched bar tested at the same temperature.



$t_r = t_n$

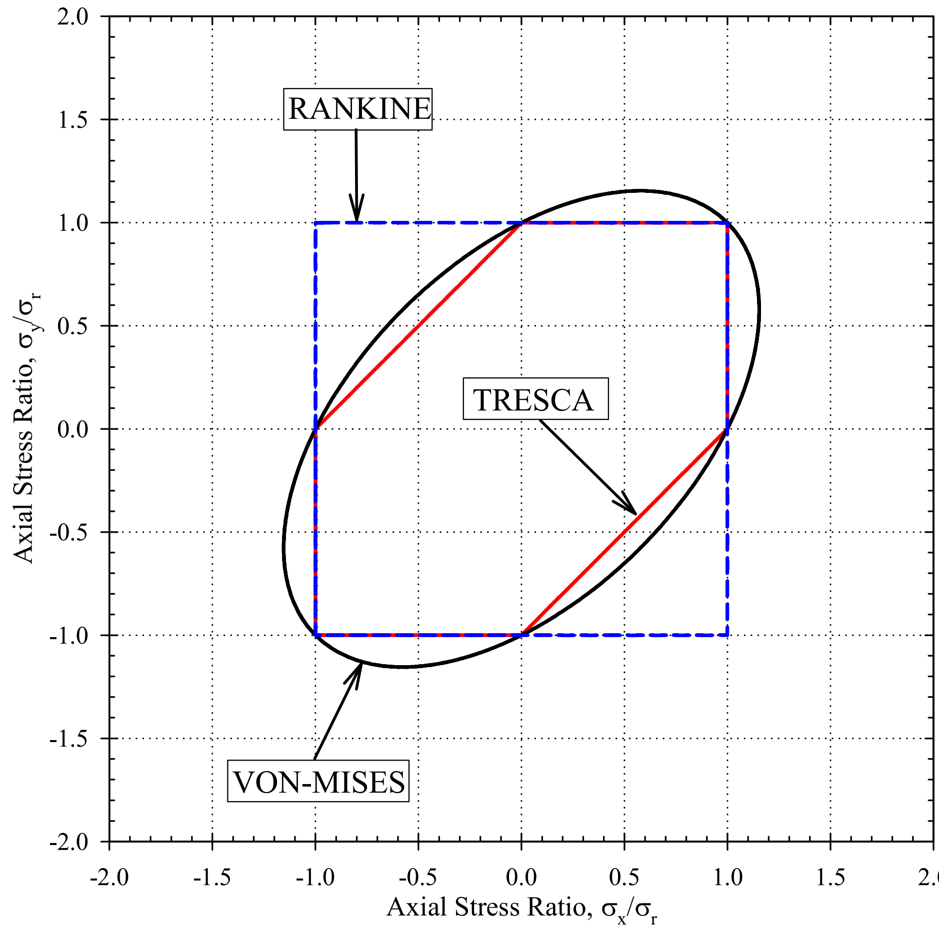
Classic approaches

- Rankine criteria, $\sigma_{p,\max} > \sigma_{uts}$
- Tresca criteria, $\tau_{\max} > \sigma_{uts}$
- Von-Mises criteria,

$$\sigma_{vm} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}$$

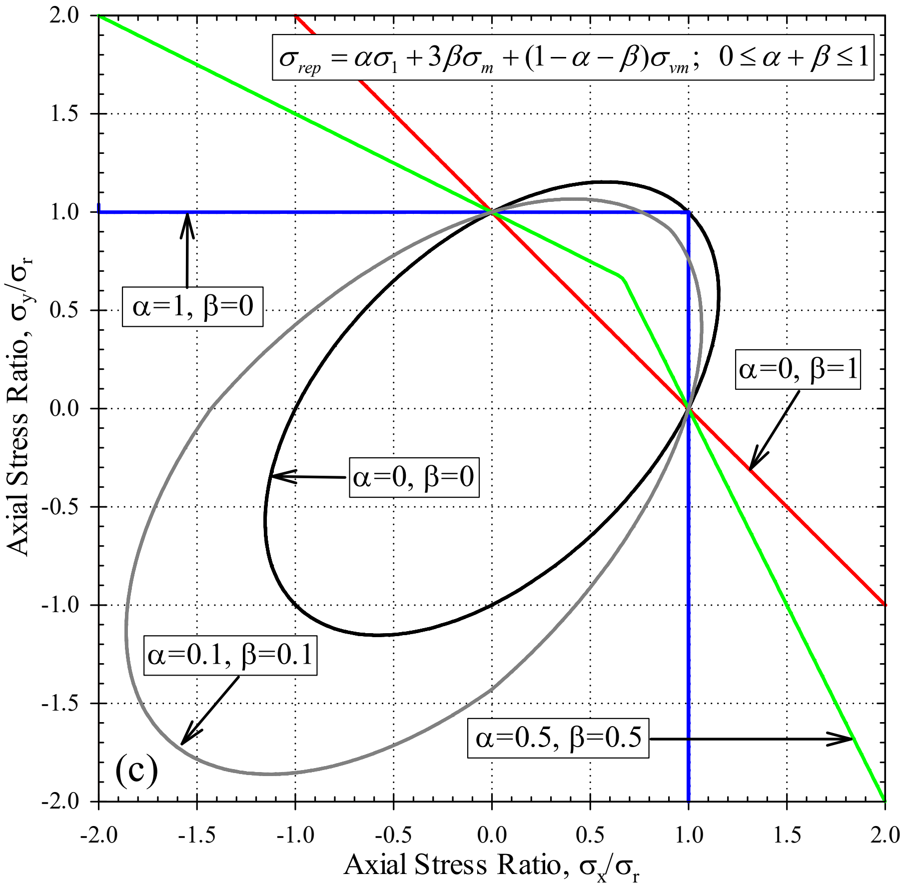
Limitations of Classic approaches

- Under equi-biaxial tension, $\sigma_x / \sigma_y = 1$ the rupture stress is non-conservative and identical to the uniaxial case.

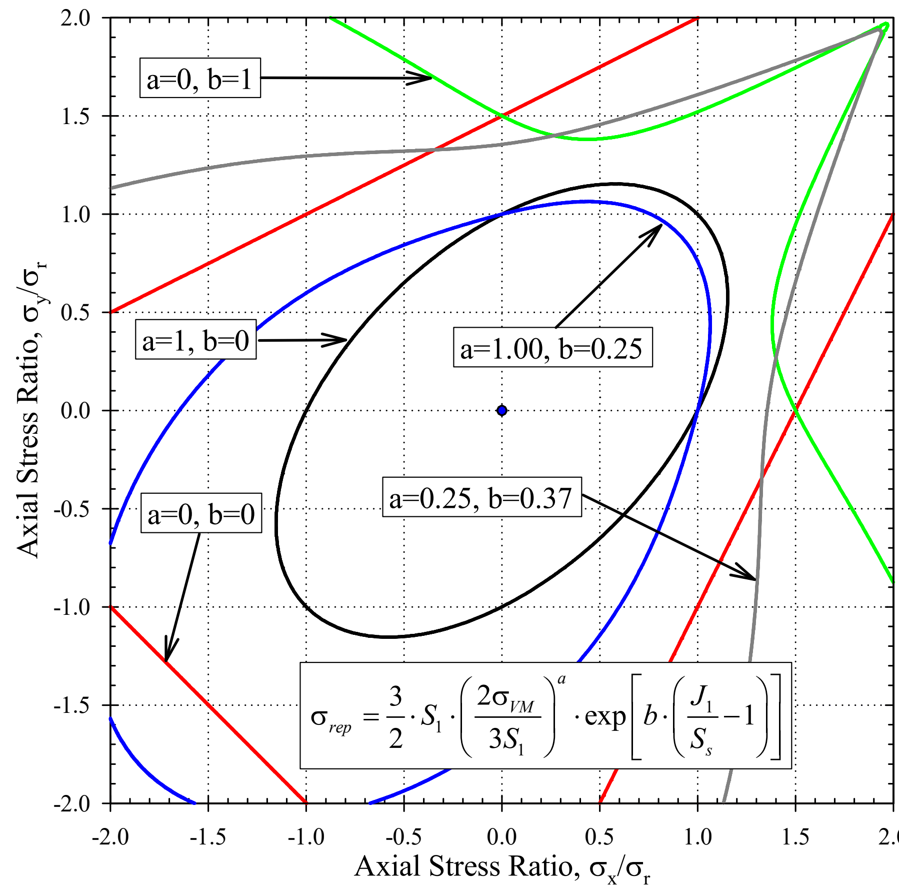


Classic function rupture surface

Representative Stress Functions



Hayhurst function rupture surface



Huddleston function rupture surface

[6] Haque, M. S., and Stewart, C. M. (2017). Selection Of Representative Stress Function Under Multiaxial Stress State Condition For Creep. *ASME Paper No. PVP2017-65296.*

Guideline to representative function selection

- ASME B&PV III (ASME Boiler and Pressure Vessel Code)
- RCC-MR (Design and Construction Rules for Power Generating Stations)
- ESIS (European Structural Integrity Society)

Stress function
- Either the Hayhurst or Huddleston function be used.
- Hayhurst function is simpler.
- Huddleston function is more flexible.

Numerical stability
- Check for infinite or imaginary condition leading to numerical instability.
- Hayhurst function is completely stable.
- Huddleston function is unstable at unstressed condition.

Material parameter calibration
- Uniaxial and Equi-biaxial tension creep tests.
- Regression analysis.

Damage mechanism
- Von-Mises stress: deformation.
- Hydrostatic stress: void growth.
- Principal stress: intergranular damage.

Incompressibility
- Constraints should be applied to enforce incompressibility.

Ref: [6]

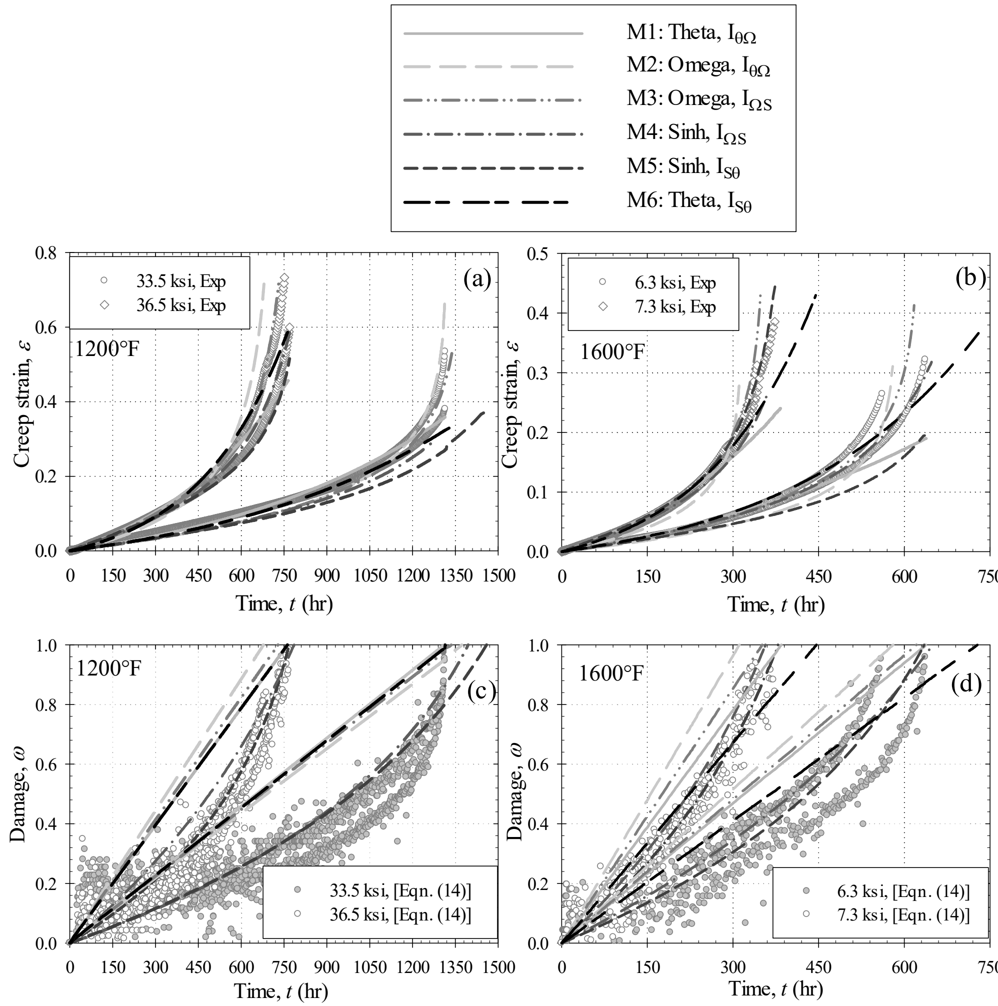
Results and recommendations

- Performance of the individual models
- Performance of the Metamodels

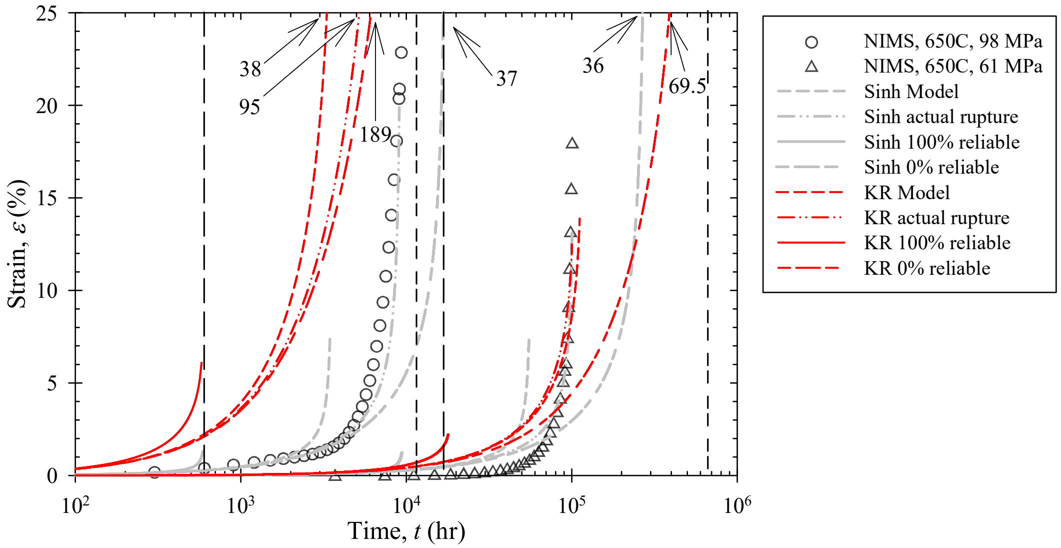
- Recommendations
  - Guideline to TTP model selection
  - Guideline to representative function selection.
  - Guideline to minimum creep strain rate model selection.
  - Guideline to CDM model selection.

- A master guideline to adaptive approach towards creep modeling.

Figure: Comparison of combinational models using Siemens data (a-b) deformation, (c-d) damage prediction for Hastelloy X at 1200°F and 1600°F

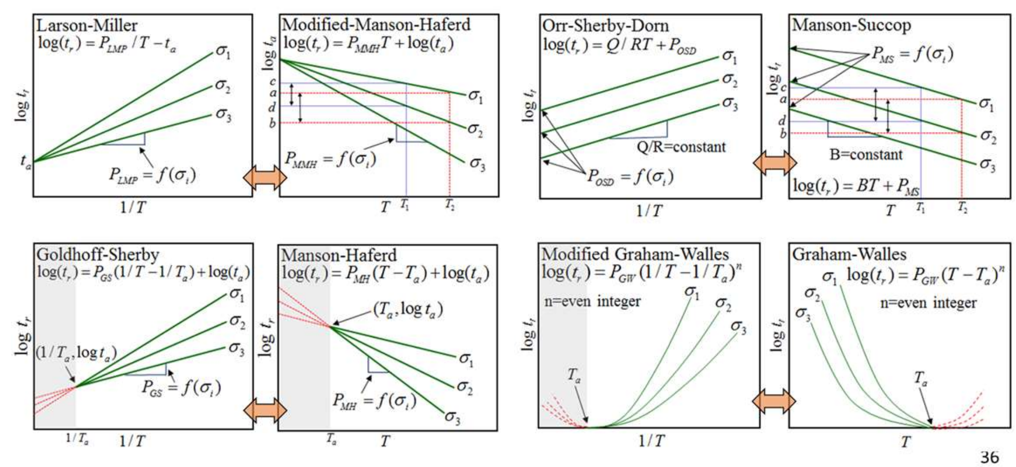


Summary



- Inclusion of **disparate data** into calibration process can significantly improve the prediction accuracy.

- A **metamodel** derived by combining and exploiting creep models where the submodels (existing and new models that are exploited to develop the metamodel) are special case can facilitate instantaneous and efficient evaluation of the submodels leading to the selection of “best” model”.



Publications

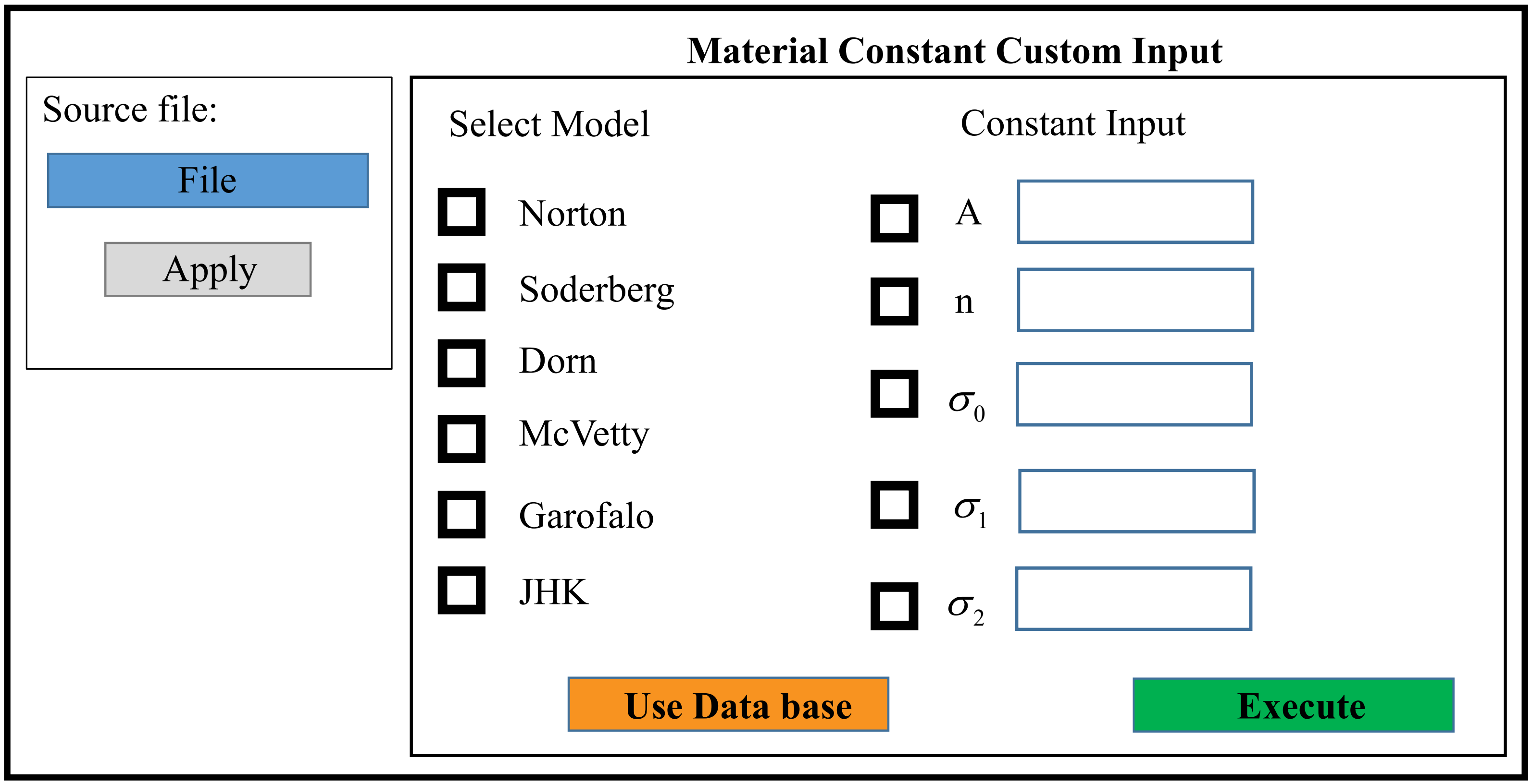
1. Haque, M. S., and Stewart, C. M. (2017). The Stress-Sensitivity, Mesh-Dependence, and Convergence of Continuum Damage Mechanics Models for Creep. **Journal of Pressure Vessel Technology**, 139(4), 041403.
2. Haque, M. S., Ramirez. C. and Stewart, C. M. (2017). Novel Metamodeling Approach For Time-temperature Parameter Models. **ASME** Pressure Vessel and Piping Conference. Paper No. PVP2017-65297. (***Award: Honorable mention***)
3. Haque, M. S., and Stewart, C. M. (2017). Selection Of Representative Stress Function Under Multiaxial Stress State Condition For Creep. **ASME** Pressure Vessel and Piping Conference. Paper No. PVP2017-65296.
4. Ramirez. C., Haque, M. S., and Stewart, C. M. (2017). Guidelines To The Assessment Of Creep Rupture Reliability For 316SS Using The Larson-miller Time-temperature Parameter Model. **ASME** Pressure Vessel and Piping Conference. Paper No. PVP2017-65816.
5. Haque, M. S., Ramirez, C., Chessa, J. F., Stewart, C. M., "A Guideline for the Assessment of Uniaxial Creep and Creep-Fatigue Data and Models", 2017 Project Review Meeting for Crosscutting Research, Gasification Systems and Rare Earth Elements Research Portfolios, NETL, Department of Energy.
6. Haynes, A. C., Haque, M. S., Stewart, C. M., "The Numerical Analysis of Equivalent Stress Functions for Multiaxial Creep Deformation, Damage, and Rupture", UTEP COURI Project, May 2017.

In progress:

1. Haque, M. S., and Stewart, C. M. (2018). The Disparate Data Problem: The Calibration of Creep Laws Across Test Type And Stress, Temperature, and Time Scales. (ready for submission)
2. Haque, M. S., and Stewart, C. M. (2018). Metamodeling Time-Temperature Parameter Models for Creep Rupture. (90% complete)
3. Perez, J., Vega, R., Haque, M., Zamorano, D., and Stewart, C. (2018). Calibration and Validation of Phenomenological Creep Deformation Laws. (90% complete)

Future Work

Software: Secondary Creep model



Ricardo Vega

Future Work

Software: Creep Deformation model

Material Constant Custom Input

Source file:

File

Apply

Select Model

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

Constant Input

σ_0

σ_1

σ_2

σ_3

σ_4

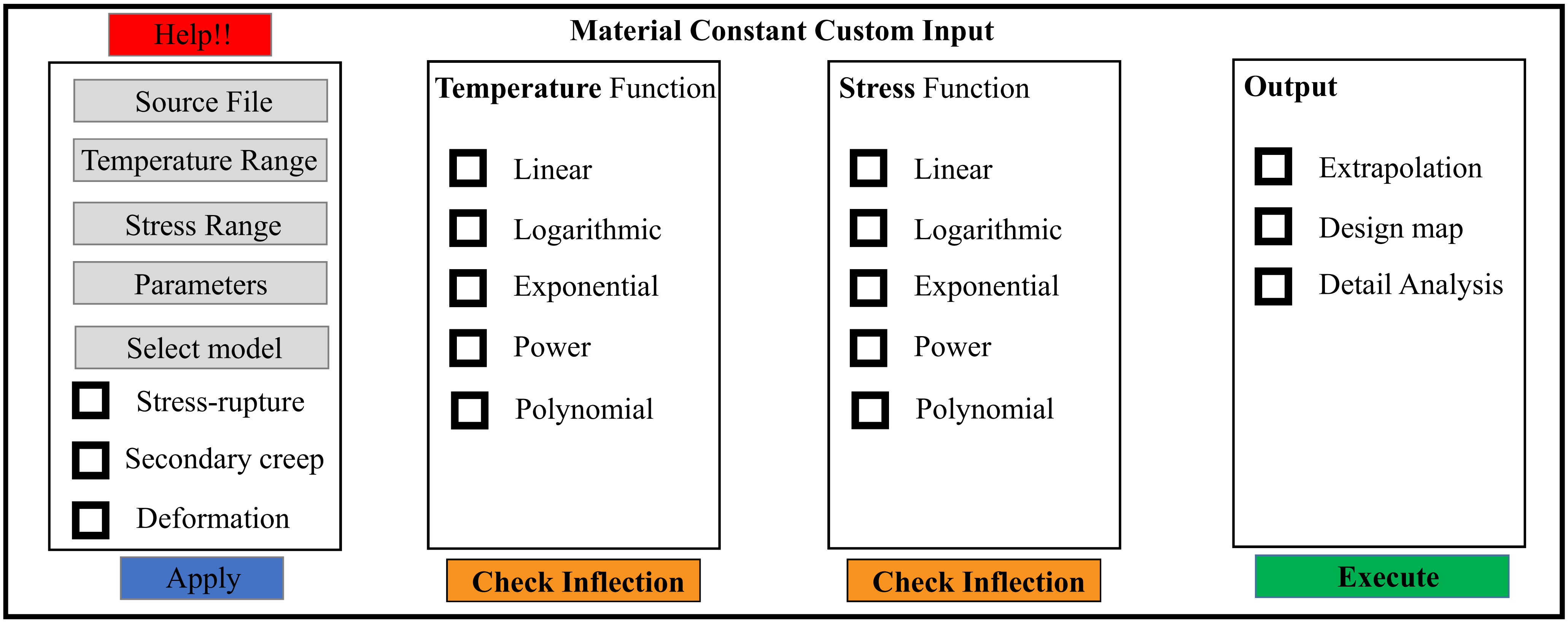
Use Data base

Execute

Jimmy Perez

Future Work

Software: Extrapolation and Design Maps



Thank you

Acknowledgement:

Department of Energy (DOE)
National Energy Technology Laboratory (NETL)
Award Number(s): DE-FE0027581

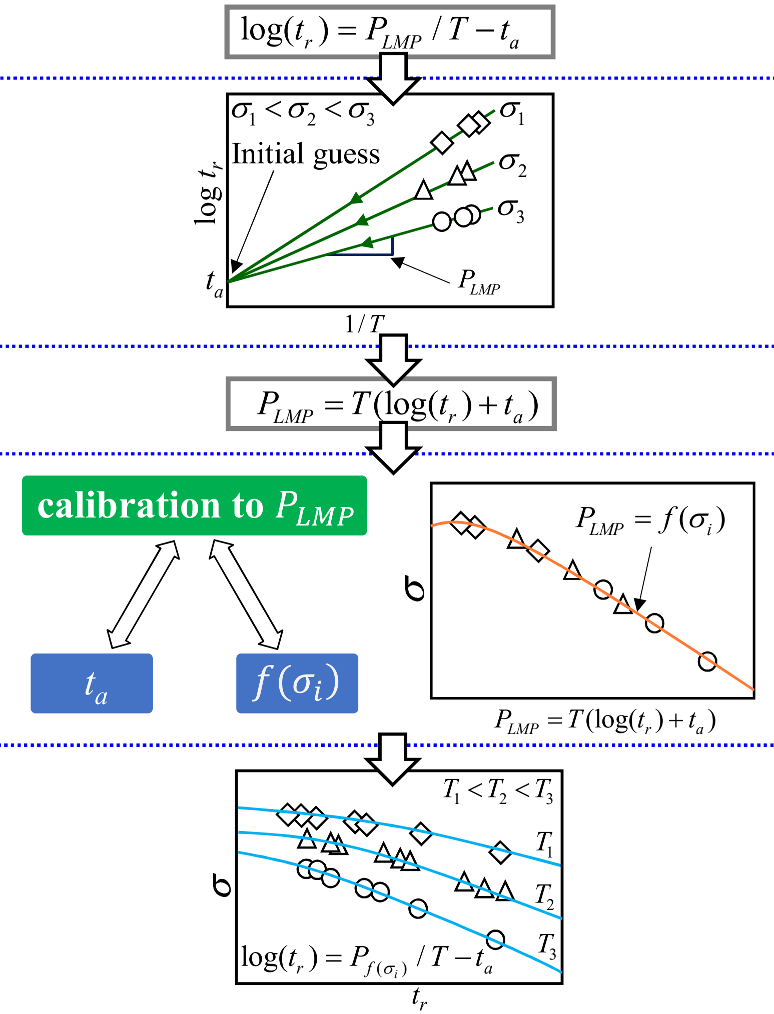
- Omer R. Bakshi

– Federal Project Manager, Crosscutting Research, NETL, U.S. DOE

UTEP MERG Research Team

Time-Temperature Parameter (TTP) Model

1. **TTP model**
2. Find initial guess constant, t_a (graphical approach)
3. Calculate P_{LMP} for each data point
4. Simultaneous calibration of constant, t_a and stress-parameter function.
5. Plot model with experimental data



Metamodel

Existing approach

- Holdsworth, 1999 (LM, MH, Mod-MH, MRM, and Mod-MRM)

$$\log(t_r) = \left\{ \sum_{k=0}^{n} \beta_k (\log[\sigma]^k) \right\} (T - T_a) + \beta_5; \quad n = 2,3,4$$

- Eno, 2008 (LM, MH, OSD, MS, and MRM)

$$\log(t_r) = \beta_0 + \beta_1 (T) + \beta_2 \log(\sigma) + \beta_3 \log(\sigma)(T)$$

$$\log(t_r) = \beta_0 + \beta_1 \left(\frac{1}{T}\right) + \beta_2 \log(\sigma) + \beta_3 \log(\sigma)\left(\frac{1}{T}\right)$$

- Seruga, 2011 (LM, MH, OSD, and MB)

$$\log(t_r) = (T - T_a.\langle q \rangle)^q (a_0 + a_1 \log(\sigma) + a_2 \log^2(\sigma))$$
$$+ \log(t_a) T^{q-1}$$

Suitable for verified material behavior.

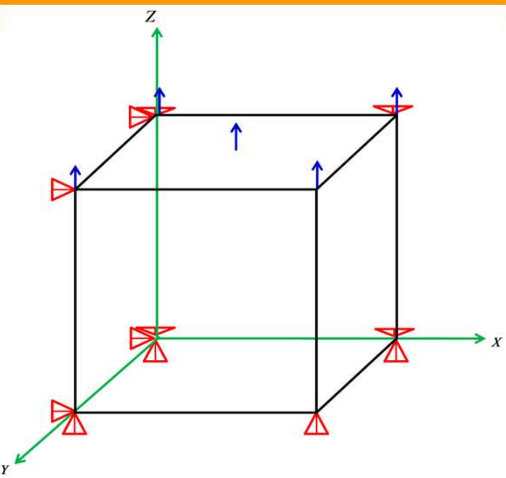
- **New approach**: (Includes 12 TTP models)

$$P_{HS}(\sigma) = \frac{\log(t_r) - \alpha_0 - \alpha_1 T^r}{(T^r - \alpha_2{}^r)^q}$$

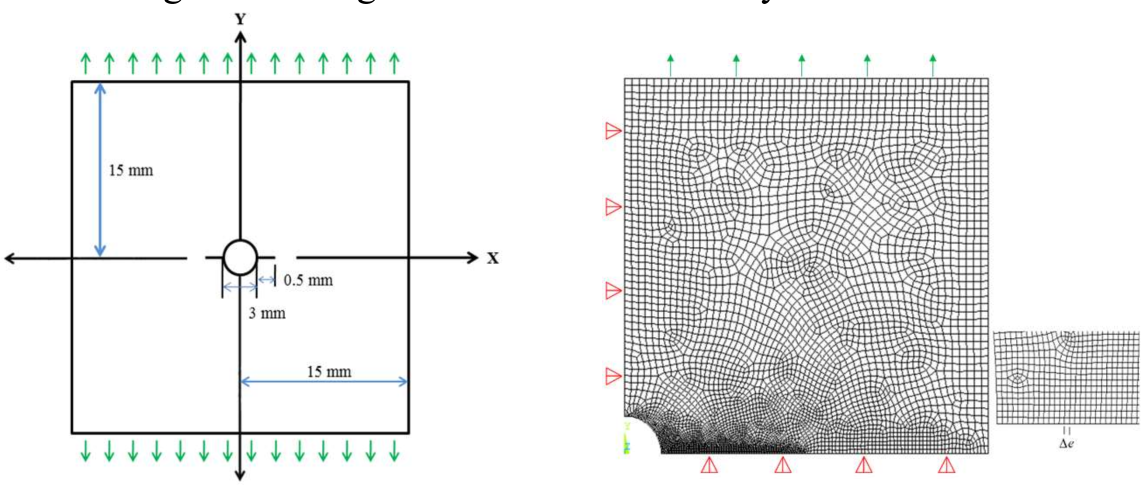
Flexible to fit any material behavior.

Task 8: Computational Analysis (2D)

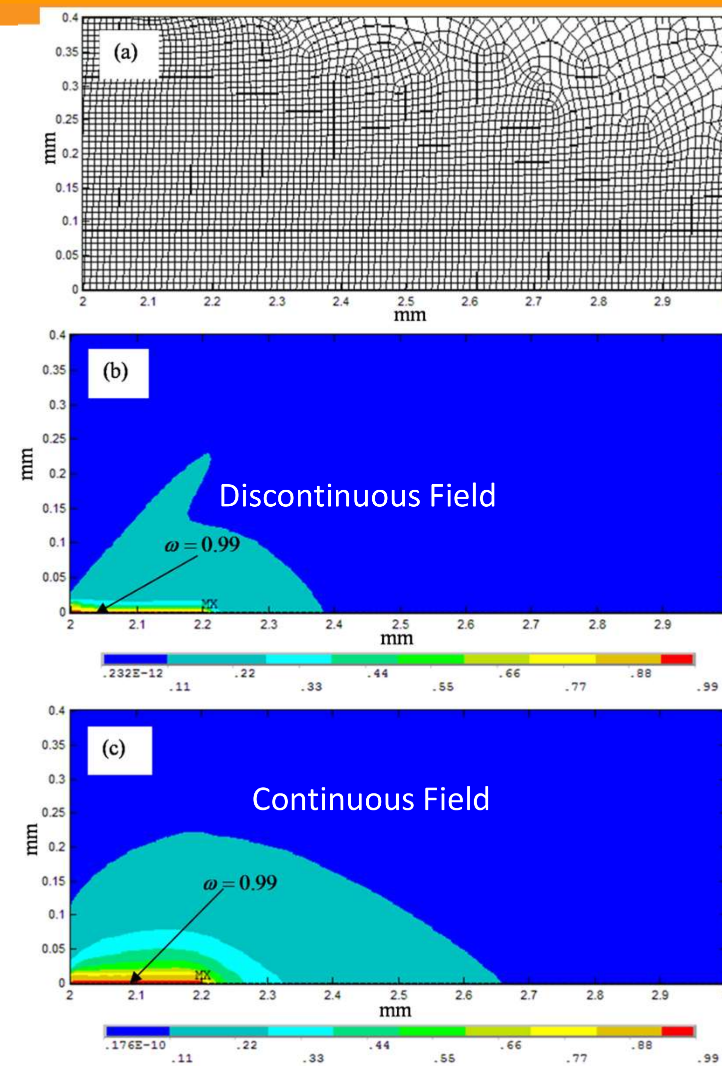
Ref: [10]



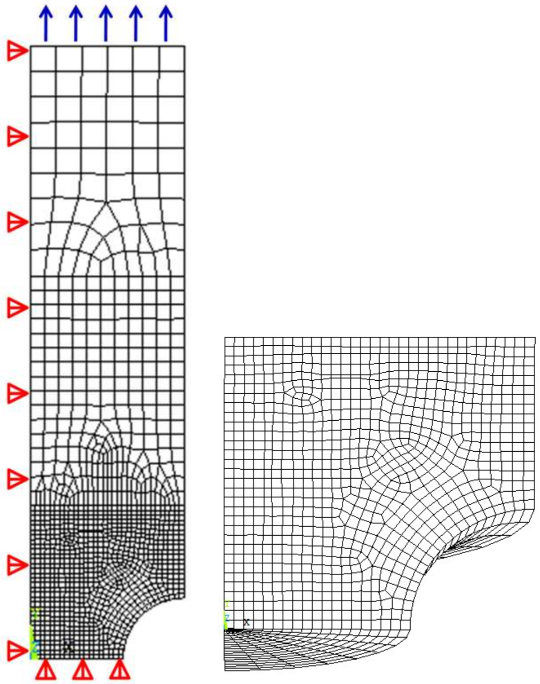
Eight node single element with boundary constraint



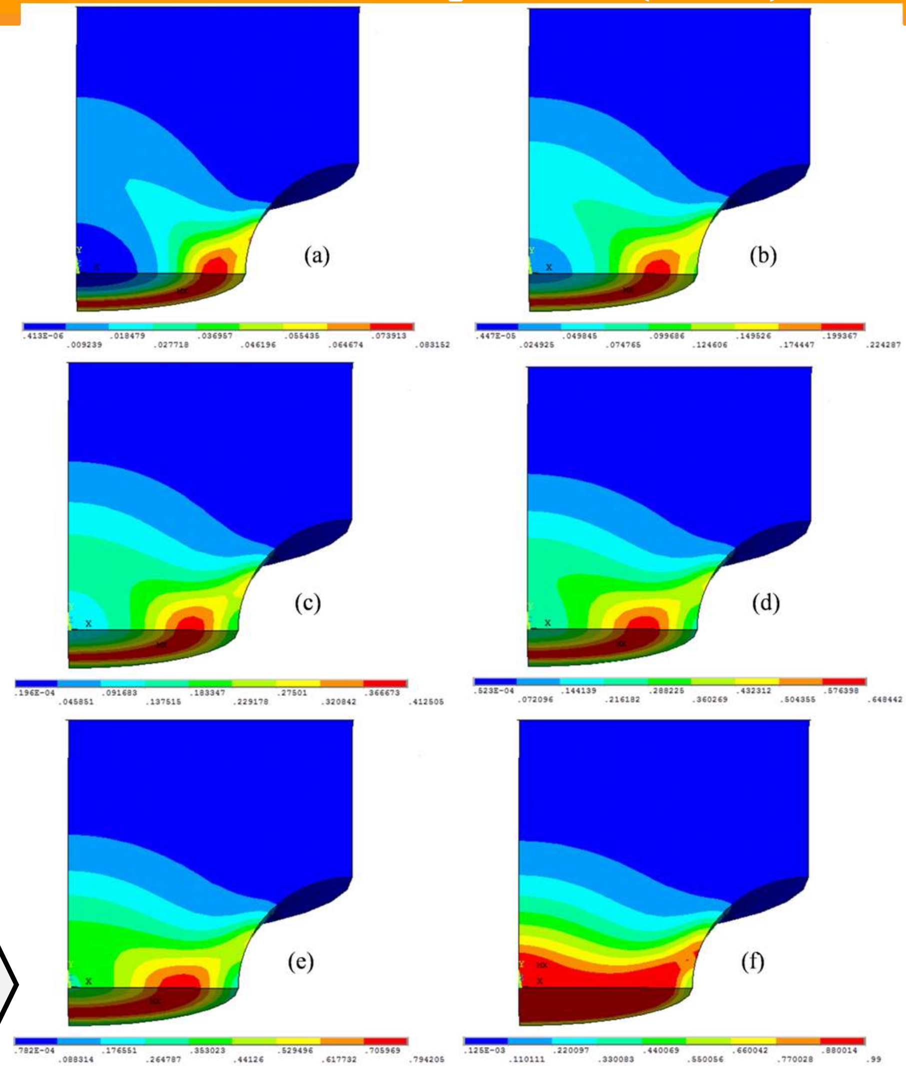
2D center-hole plate (a) dimensions, (b) ANSYS mesh (=0.05 mm)



Task 8: Computational Analysis (3D)



ANSYS FEM mesh of Bridgeman notch specimen



Sinh damage at 250 MPa and 700°C (a) 50 hr, (b) 200 hr, (c) 400 hr, (d) 600 hr, (e) 700 hr, and (f) 832 hr