Development of Creep Strain Model of Alloy 690 Material

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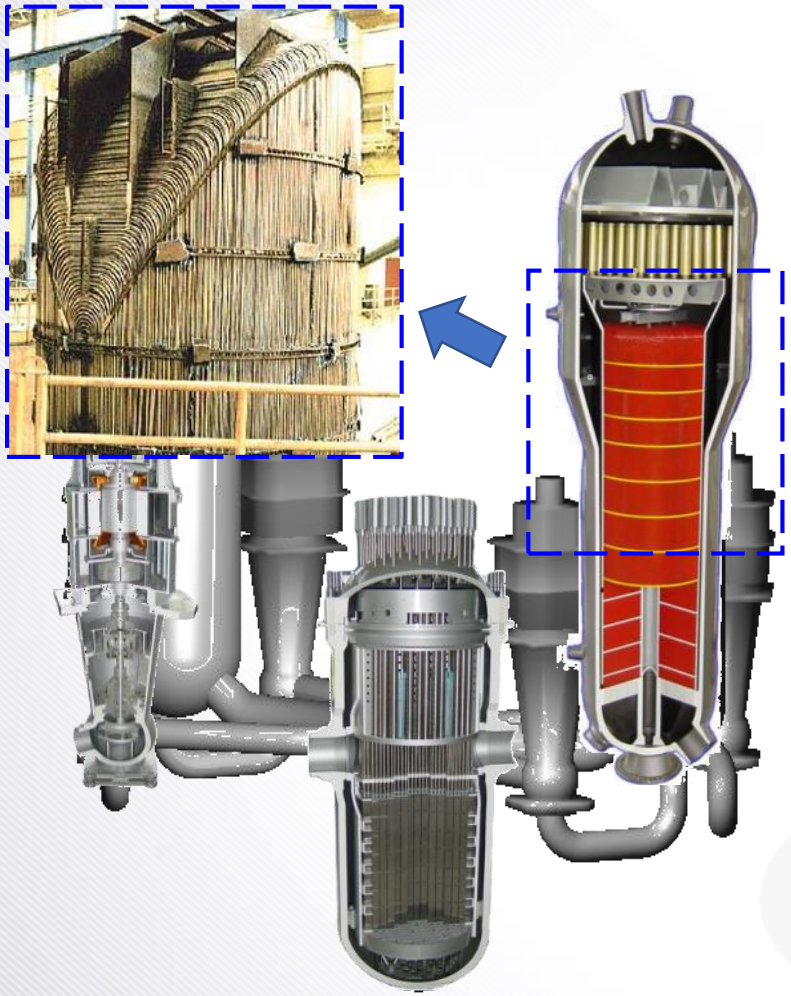
01 Background



Primary Pressure Boundary Structure in Nuclear Power Plant

- **Creep**
  - **Above 0.3–0.4 Times Melting Temperature**
  - **Irreversible Time-dependent Nonlinear Deformation Process, Dependent on Temperature ,Stress and Time**
- **Steam Generator (SG) Tubes in Postulated Severe Accidents**
  - **Rapid Changes in Pressure and Temperature → Extensive Plastic Deformation → Creep is a essential failure mechanism.**
- **SG material: Inconel 690, a Ni–Cr–Fe Alloy, with Cr Content of up to 30 wt% to Improve Corrosion Resistance**
- **Creep model for Inconel 690 is necessary for SG tubes integrity assessment.**

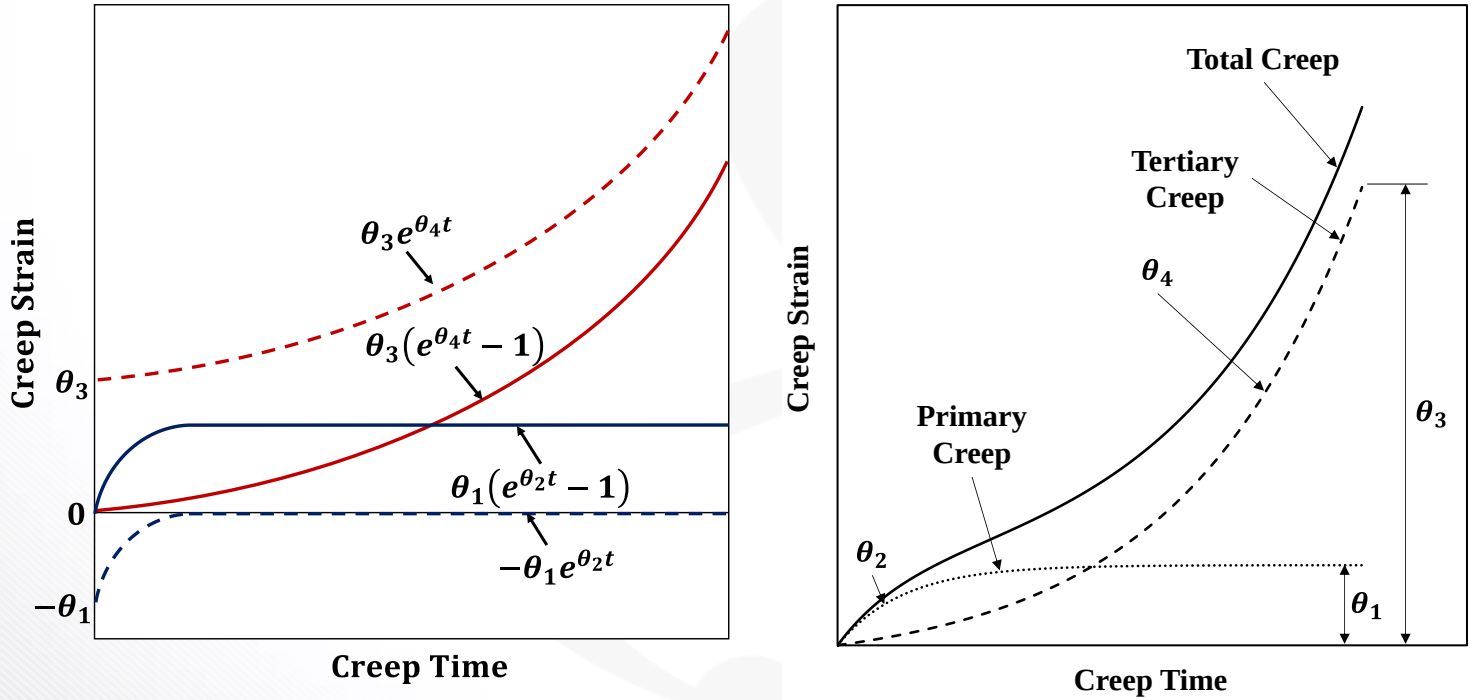
01 Theta (θ) Projection Method

θ Projection Method: A Creep-modeling Method

- **Four θ Coefficients which Obtained from Regression Analysis of Experimental Creep Curve**

$$\varepsilon = \theta_1\left(1 - e^{-\theta_2 t}\right) + \theta_3\left(e^{\theta_4 t} - 1\right)$$

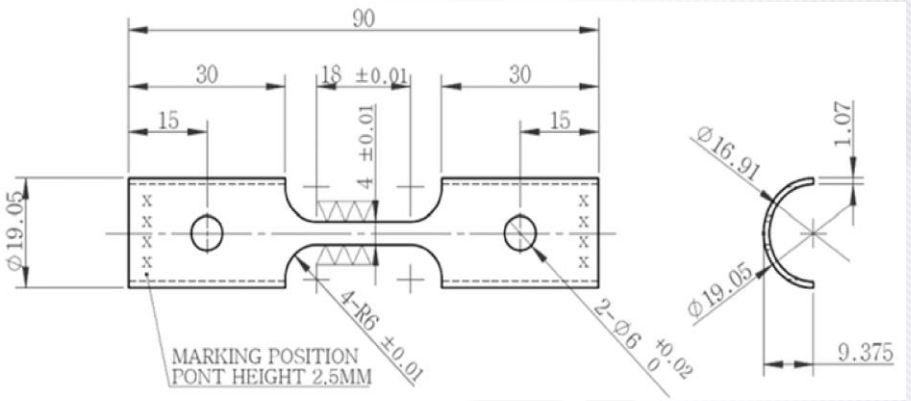
$$log\theta_i = a_i + b_i\sigma + c_i T + d_i\sigma T$$



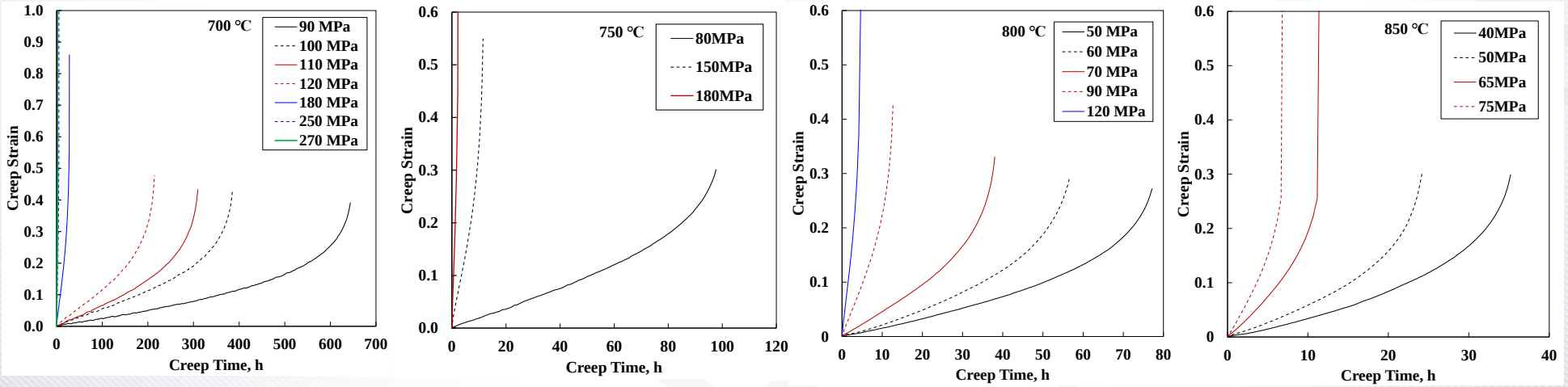
Physical Meaning of θ Parameters

02 Creep Test for Inconel 690

- **Creep Test Condition**
  - **Temperature Range: 650 ~ 850 °C**
  - **Tube-type Specimens**
    (19.05 mm in Outside Diameter, 1.07 mm Thick)
  - **Electromechanical Testing Machine**
    (R&B® Model RB-301)



Creep Test Specimen



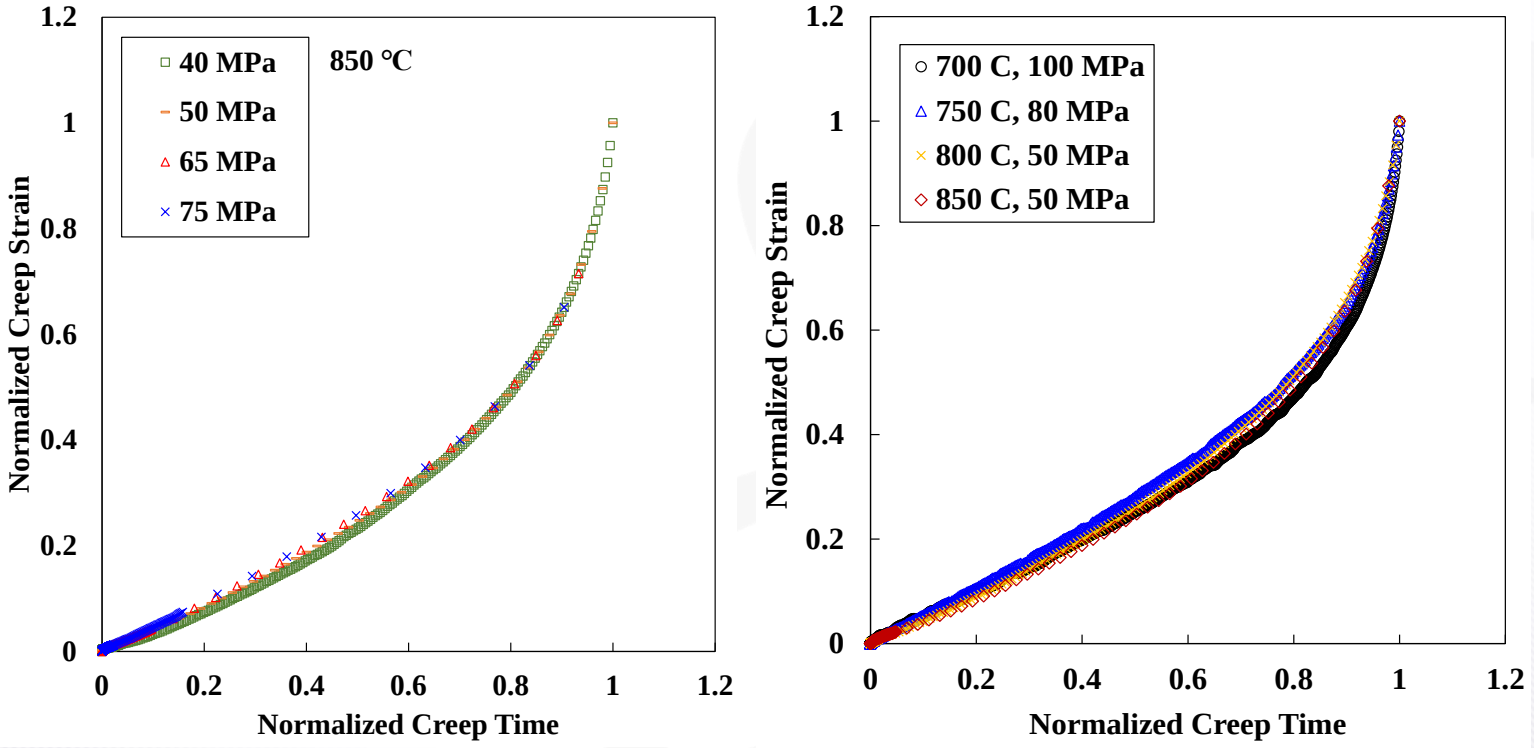
Creep Curve for Inconel 690 Material

02 Normalized Creep Curve

- **Creep Curve Normalized with Reference Time (t_{rr}) and Reference Strain (ε_{rr})**

$$\ln t_{rr} = 26.399 + 4.097 \times 10^{-2}\sigma - 2.486 \times 10^{-2}T - 1.018 \times 10^{-4}\sigma T$$

$$\ln t_{rr} = 1.875 - 2.088 \times 10^{-2}\sigma - 4.113 \times 10^{-3}T + 3.453 \times 10^{-5}\sigma T$$



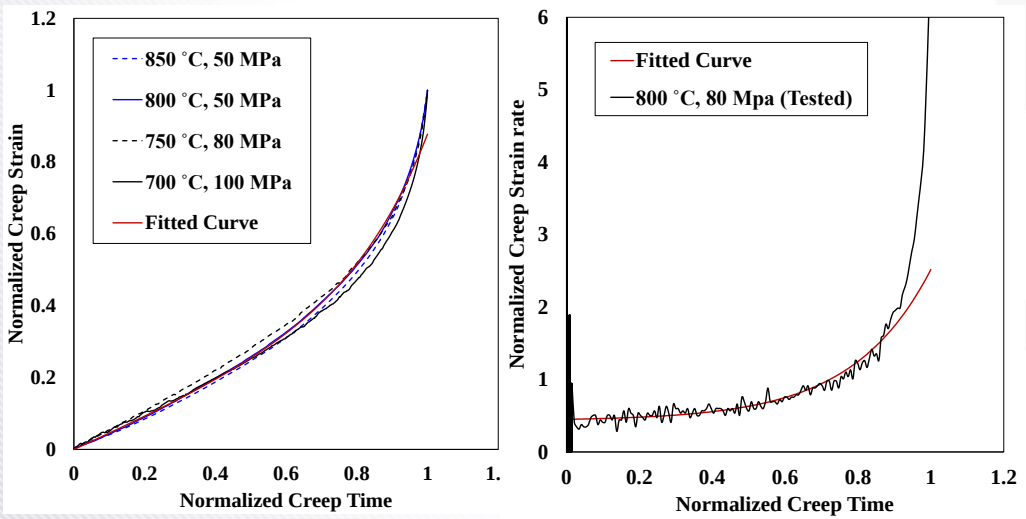
Normalized Creep Curves for Stress and Temperature Change

02 Novel Modified θ Projection Method

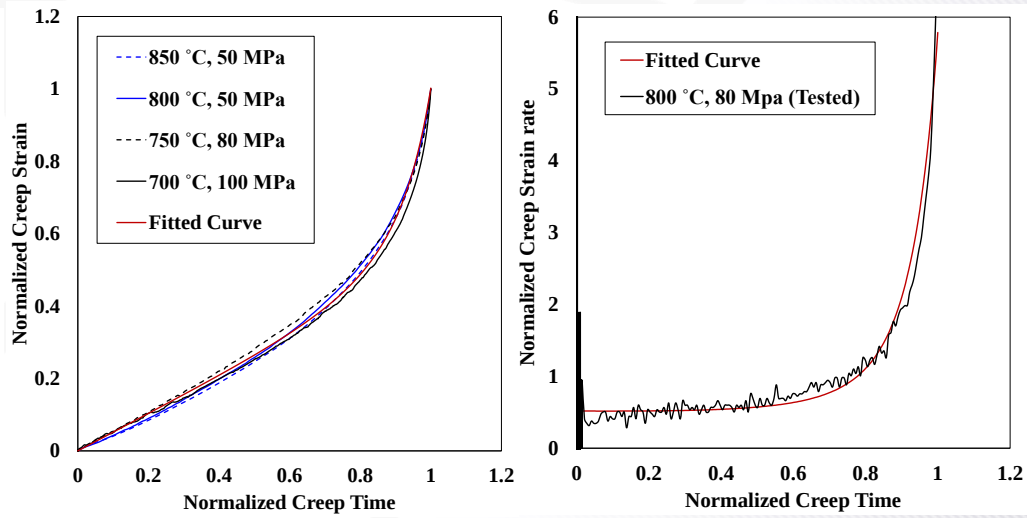
- **To Fit experimental Creep Curves in All Three Creep Stages with Improved Accuracy Than Original θ Projection Method**

$$\varepsilon = \theta_1\left(1 - e^{-\theta_2 t}\right) + \theta_3\left(e^{\theta_4 t^{\theta_5}} - 1\right)$$

$$\theta_{1,3}^{T,\sigma} = \epsilon_{rr} \cdot \theta_{1,3};\ \theta_2^{T,\sigma} = \frac{\theta_2}{t_{rr}};\ \theta_4^{T,\sigma} = \frac{\theta_4}{t_{rr}^{\theta_5}};\ \theta_5^{T,\sigma} = \theta_5$$



Curve Fitting Result Based on Original θ Projection Method

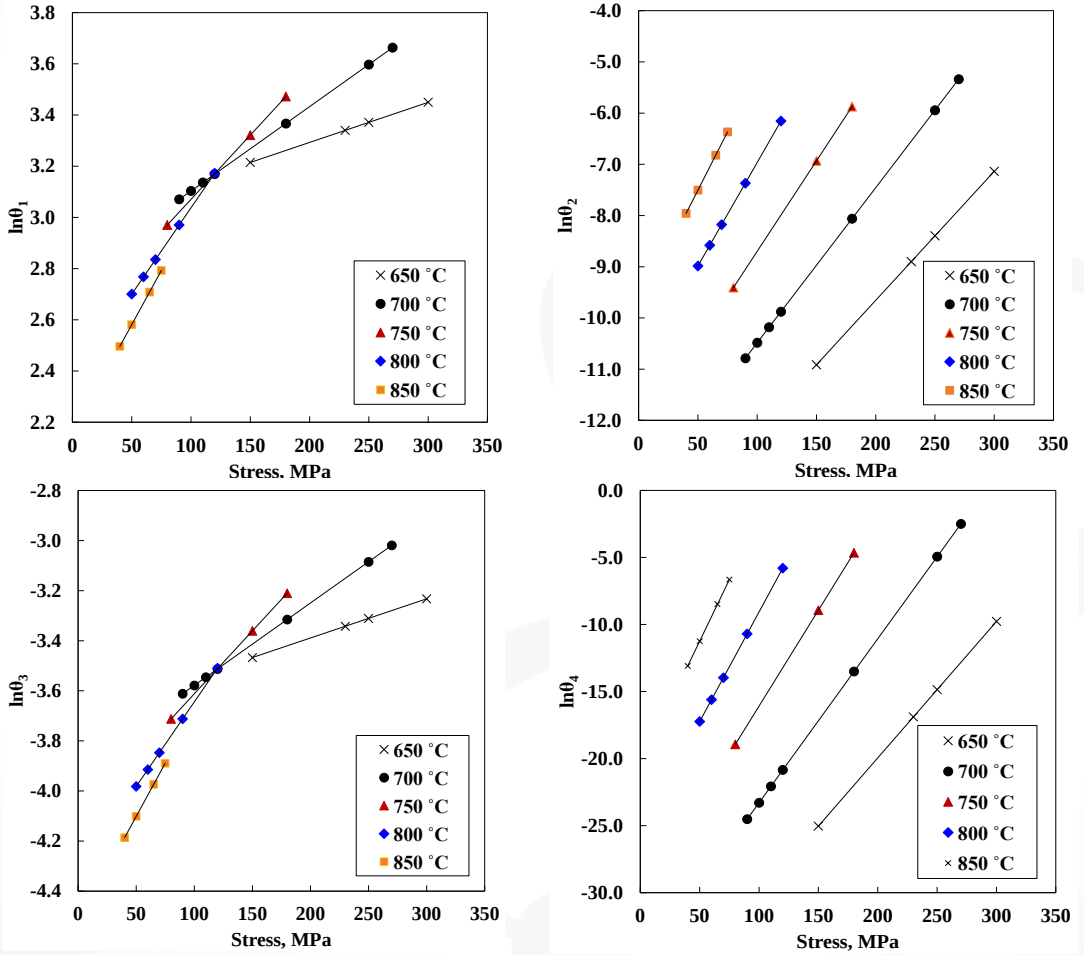


Curve Fitting Result Based on Modified θ Projection Method

02 Novel Modified θ Projection Method (2)

Relationship between θ Coefficient and Stress

Linear Function of Temperature and Stress in Linear-logarithm Coordinate



θ Coefficient Distribution with Stress for Different Temperatures

02 Creep Strain Model for Inconel 690

Creep Strain Model for Inconel 690 Using Modified θ Projection Method

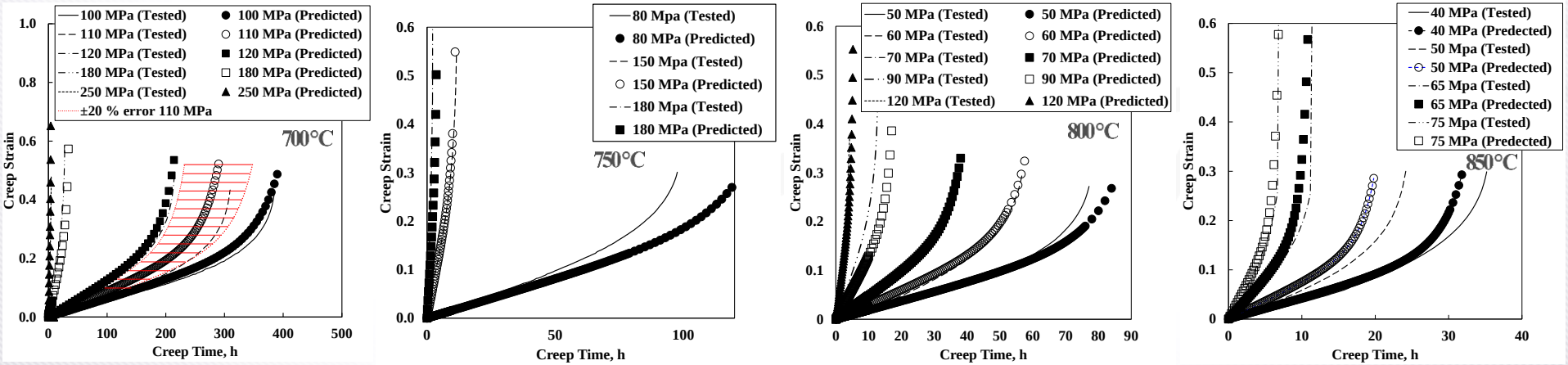
$$\varepsilon = \theta_1\left(1 - e^{-\theta_2 t}\right) + \theta_3\left(e^{\theta_4 t^{\theta_5}} - 1\right)$$

θ_1	θ_2	θ_3	θ_4	θ_5
2.45	0.22	0.06	2.32	4.95

$$\theta_{1,3}^{T,\sigma} = \epsilon_{rr} \cdot \theta_{1,3};\ \theta_2^{T,\sigma} = \frac{\theta_2}{t_{rr}};\ \theta_4^{T,\sigma} = \frac{\theta_4}{t_{rr}^{\theta_5}};\ \theta_5^{T,\sigma} = \theta_5$$

$$\ln t_{rr} = 26.399 + 4.097 \times 10^{-2}\sigma - 2.486 \times 10^{-2}T - 1.018 \times 10^{-4}\sigma T$$

$$\ln t_{rr} = 1.875 - 2.088 \times 10^{-2}\sigma - 4.113 \times 10^{-3}T + 3.453 \times 10^{-5}\sigma T$$



Creep Strain Prediction Result Using Creep Strain Model for Inconel 690

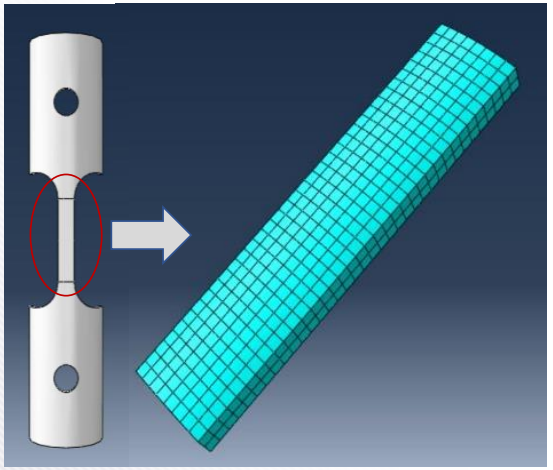
02 Simulation of Creep Strain

- **Implementation of Proposed Creep Strain Model Using ABAQUS User Subroutine**
- **Creep Strain Increment**

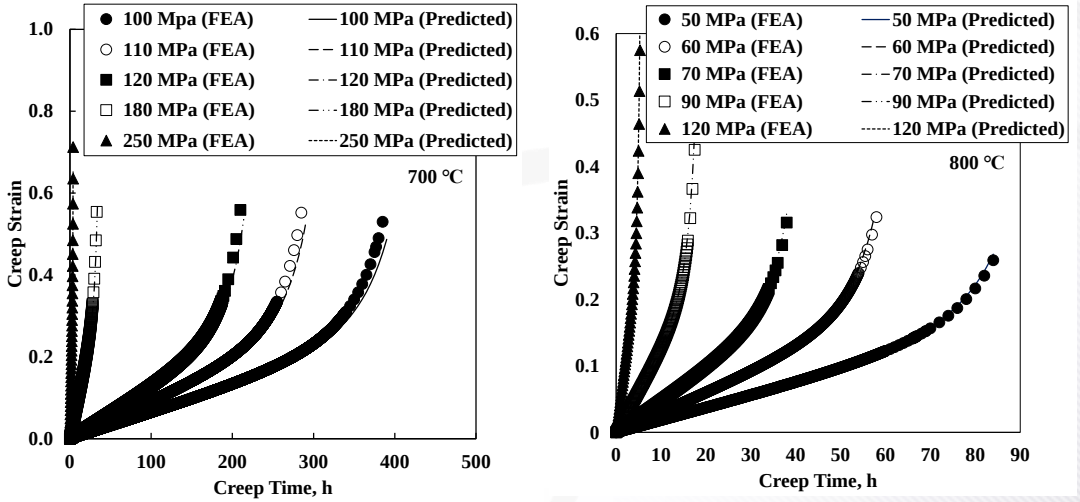
$$\Delta\varepsilon = \frac{d\epsilon}{dt}\Delta t = \left[\theta_1\theta_2 e^{-\theta_2 t} + \theta_3\theta_4\theta_5 t^{\theta_5-1} e^{\theta_4 t^{\theta_5}}\right]\Delta t$$

- **Derivative of Creep Strain Increment with Respect to Stress**

$$\frac{d\Delta\varepsilon}{d\sigma}$$



FE Mesh



Validation of User Subroutine

03 SUMMARY

- A modified θ projection method was proposed to fit creep curves in all three creep stages.
- A novel creep strain model for Inconel 690 SG tube material was proposed using proposed modified θ projection method.
- The proposed creep strain model for Inconel 690 SG tube material was implemented to the creep user subroutine for the commercial FEA code to predict the creep behavior of SG tubes.