Inelastic Deformation of a Panel Subject to Hypersonic Loads

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Collaboration with:
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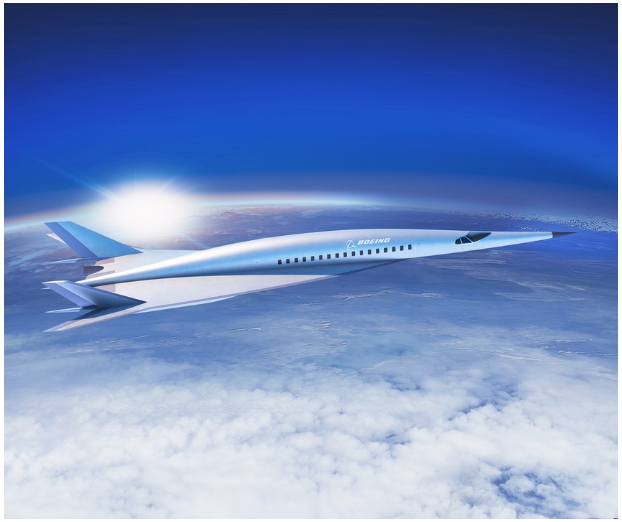
Jose A. Camberos, Air Force Research Lab

Monday, January 27, 2020

Motivation

- Reusable high speed vehicles are an active area of interest:
  - Commercial
  - Defense
  - Scientific



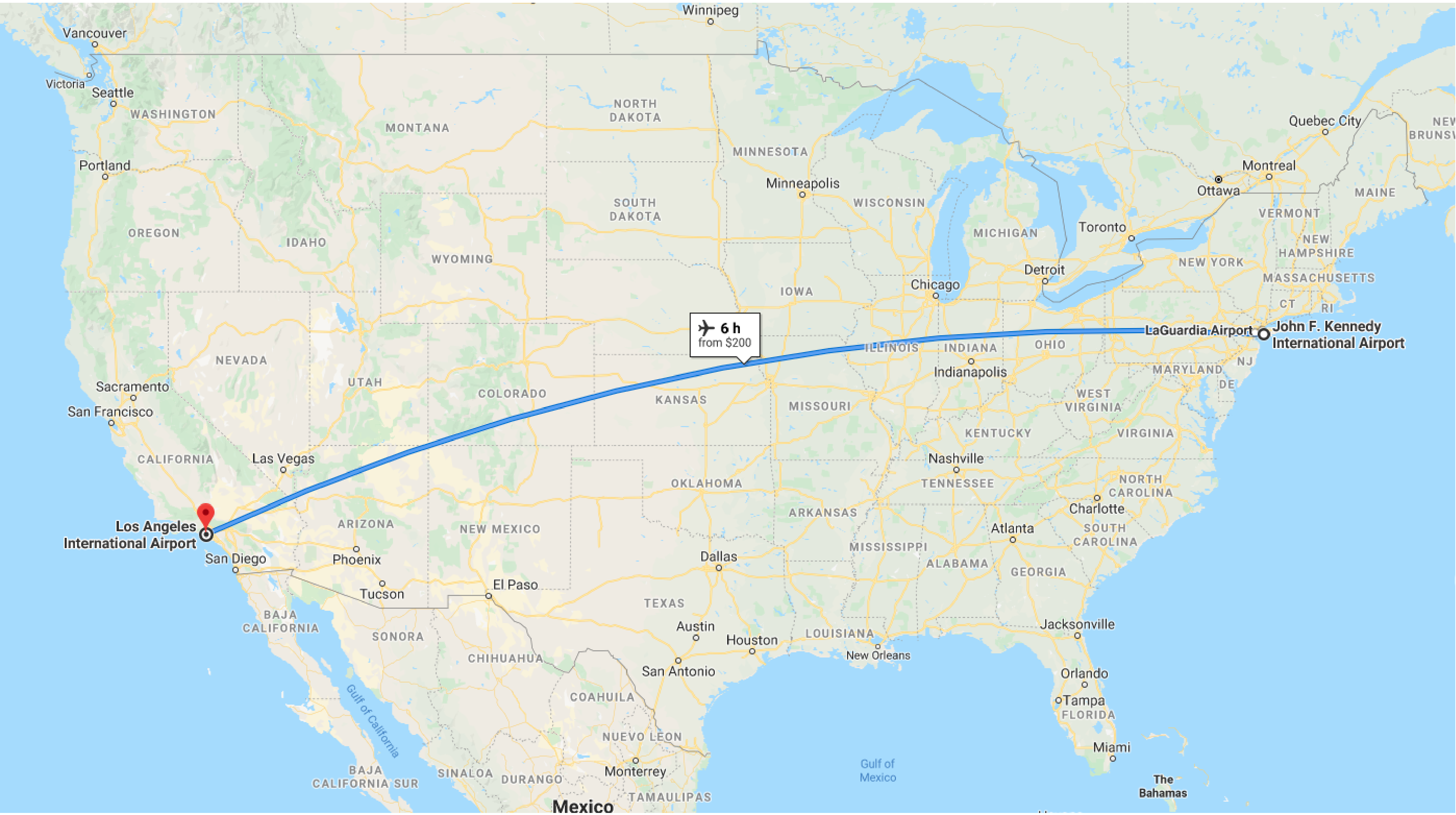
Concept Boeing Transport. Image from [1].

Concept Lockheed Martin Reconnaissance Plane. Image from [2].

Generation Orbit X-60A. Image from [3]

Motivation

- How fast is *hypersonic*?



Map from Google Maps® maps.google.com

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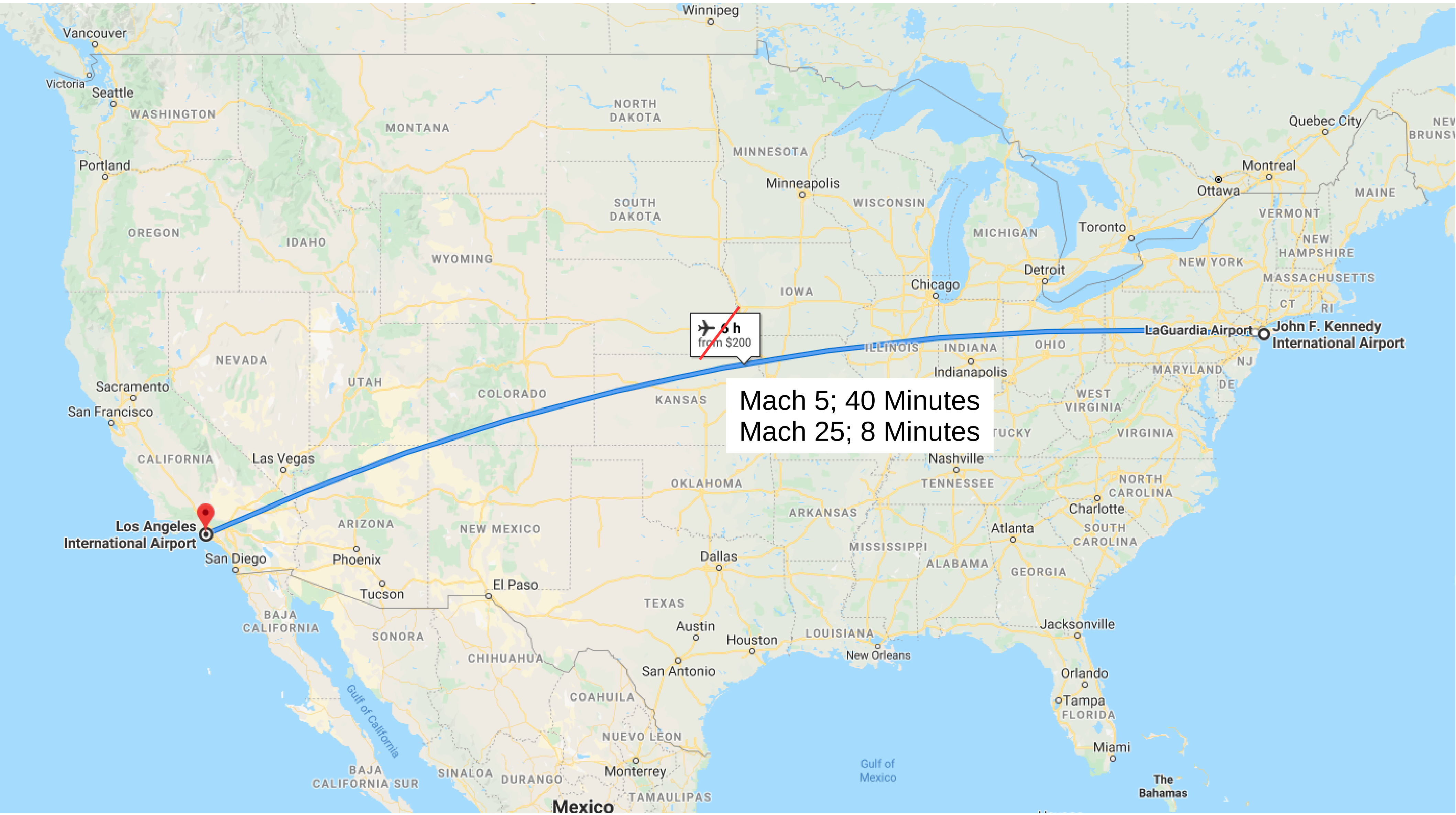

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Overview

- Motivation
- Background
- Problem Set Up
  - 1D Analytical Bar
  - Canonical Panel
- Results
  - 1D Analytical Bar
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- Closing Remarks
- Future Work

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Background

- Skin temperatures can exceed 1220º F (933 K) [4]
  - Greater than solidus temperature of most Aluminium alloys [5]
  - Within range where creep observed for Titanium alloys [6,7]

- Permanent deformation seen on X-15 after flights

X-15.
Image from NASA, Photo ID: E-5251; public domain.

Deformed leading edge after flight.
Image from [4].

Background

- Temperature-dependent models investigated [9, 10,12-16]

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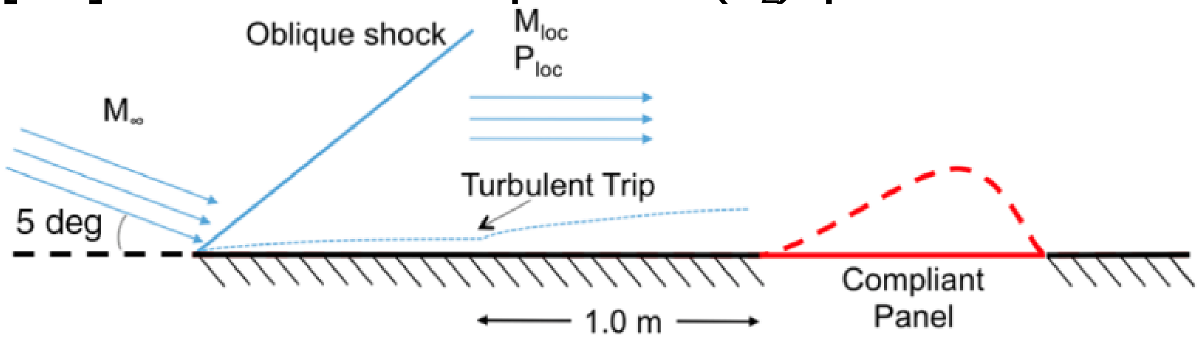
- LaFontaine et al. [16] considered a plastic (J_2) panel in multiple flows cycles



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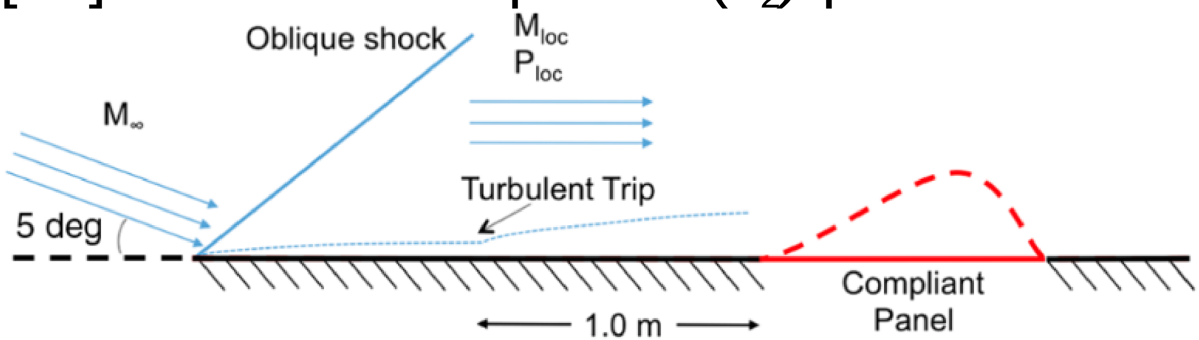
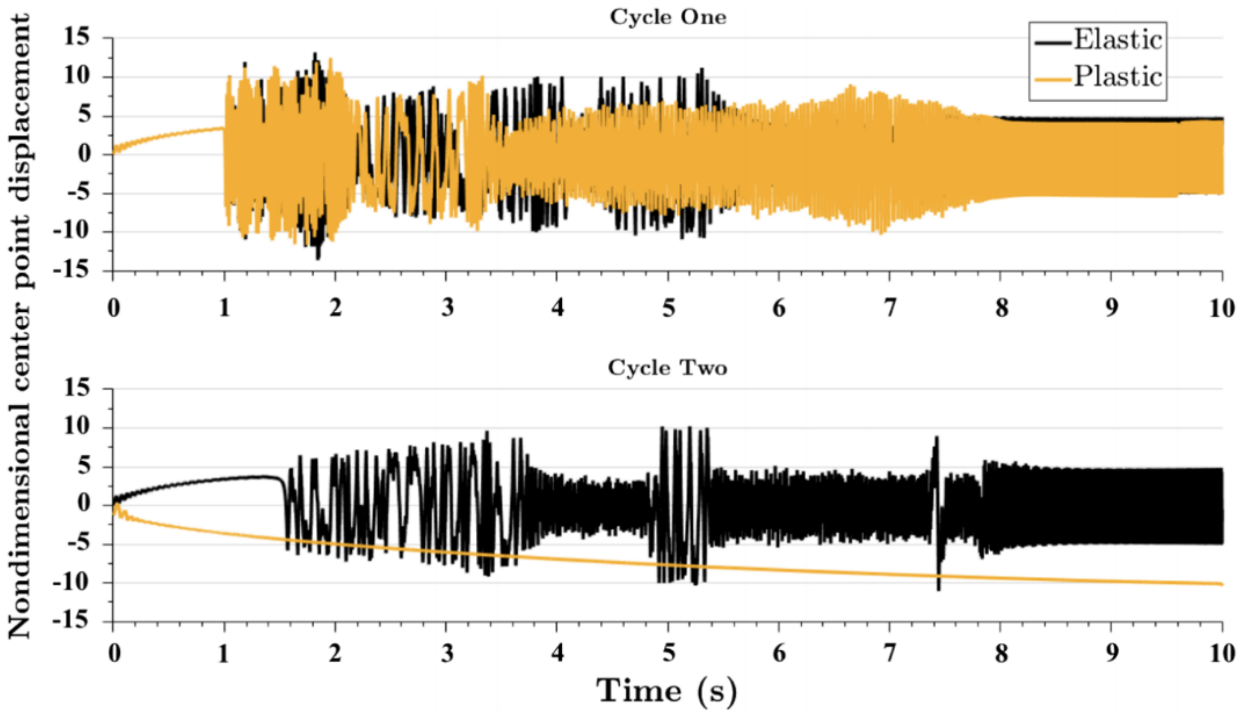


- Plastic deformation changes panel's in-flight behavior



Background

- Want to model temperature-dependent inelasticity below the yield strength
- Using a finite-strain Norton creep model [8]

$$\gamma^{cr} = \bar{A} e^{\frac{-Q}{RT}} \left(\frac{||\tau^{dev}||}{\sigma_0} \right)^{c_1}$$

$$\begin{aligned}
\bar{A} &= \text{ Relaxation Rate} \\
\sigma_0 &= \text{ Reference Stress} \\
c_1 &= \text{ Stress Exponent} \\
Q &= \text{ Activation Energy} \\
R &= \text{ Universal Gas Constant} \\
\gamma^{cr} &= \text{ Creep Strain Rate} \\
\tau &= \text{ Kirchoff Stress Tensor}
\end{aligned}$$

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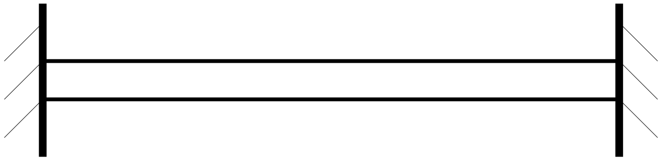
Problem Set Up : 1D Analytical Bar

- Bar fixed on both ends
  - Represents a strip of paneling



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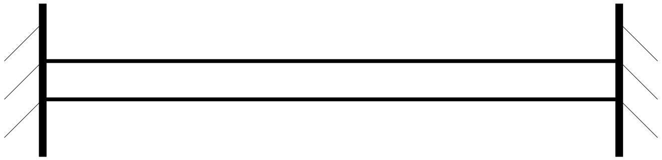

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- Additive strain decomposition

$$\epsilon^T = \epsilon^e + \epsilon^\theta + \epsilon^c = 0$$
$$\Rightarrow \epsilon^e = -\left(\epsilon^\theta + \epsilon^c\right)$$

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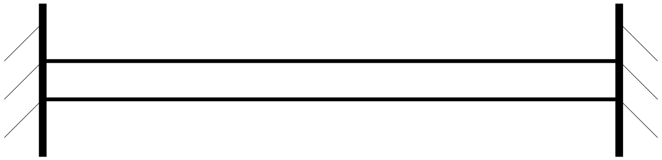

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$$\dot{\epsilon^c} = \bar{A} e^{\frac{-Q}{R\theta(t)}} \left(\frac{E||\alpha_L(\theta(t) - \theta_0) + \epsilon^c||}{\sigma_0} \right)^{c_1} \operatorname{sgn}\left(-E\left(\alpha_L(\theta(t) - \theta_0) + \epsilon^c\right)\right)$$

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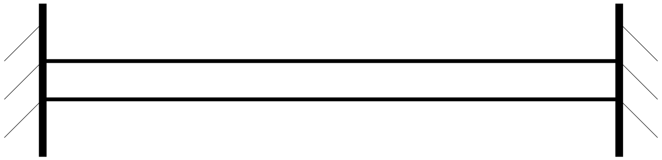

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- Solve over two “flights”
  - Each flight consists of heating, cruise, and cooling phases

Problem Set Up : 1D Analytical Bar

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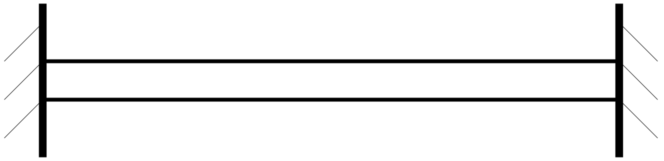
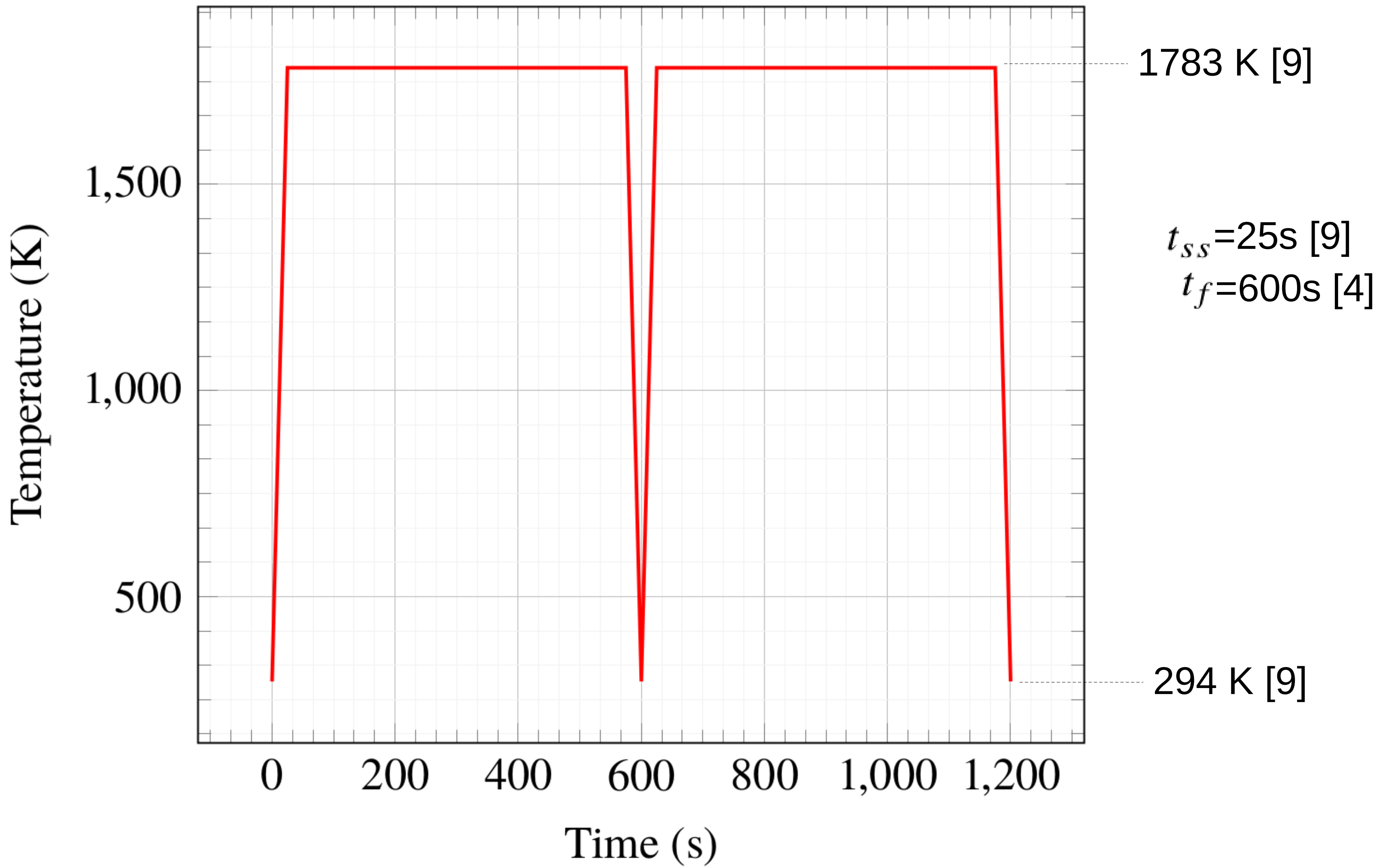
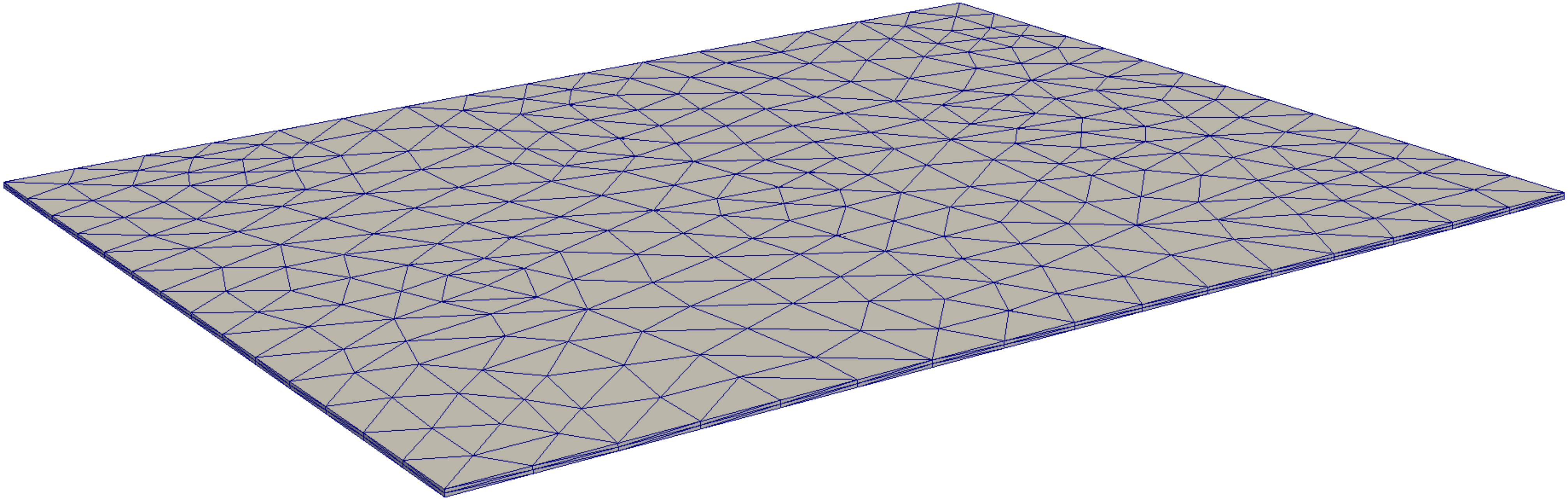


- Prescribed Temperature:



Problem Set Up : Canonical Panel

- Representative panel with linearly increasing load over 25s [9]:
  - Temperature: 294 K → 1783 K
  - Pressure: 0.0 Pa → 85.5 kPa
- Front and back fixed



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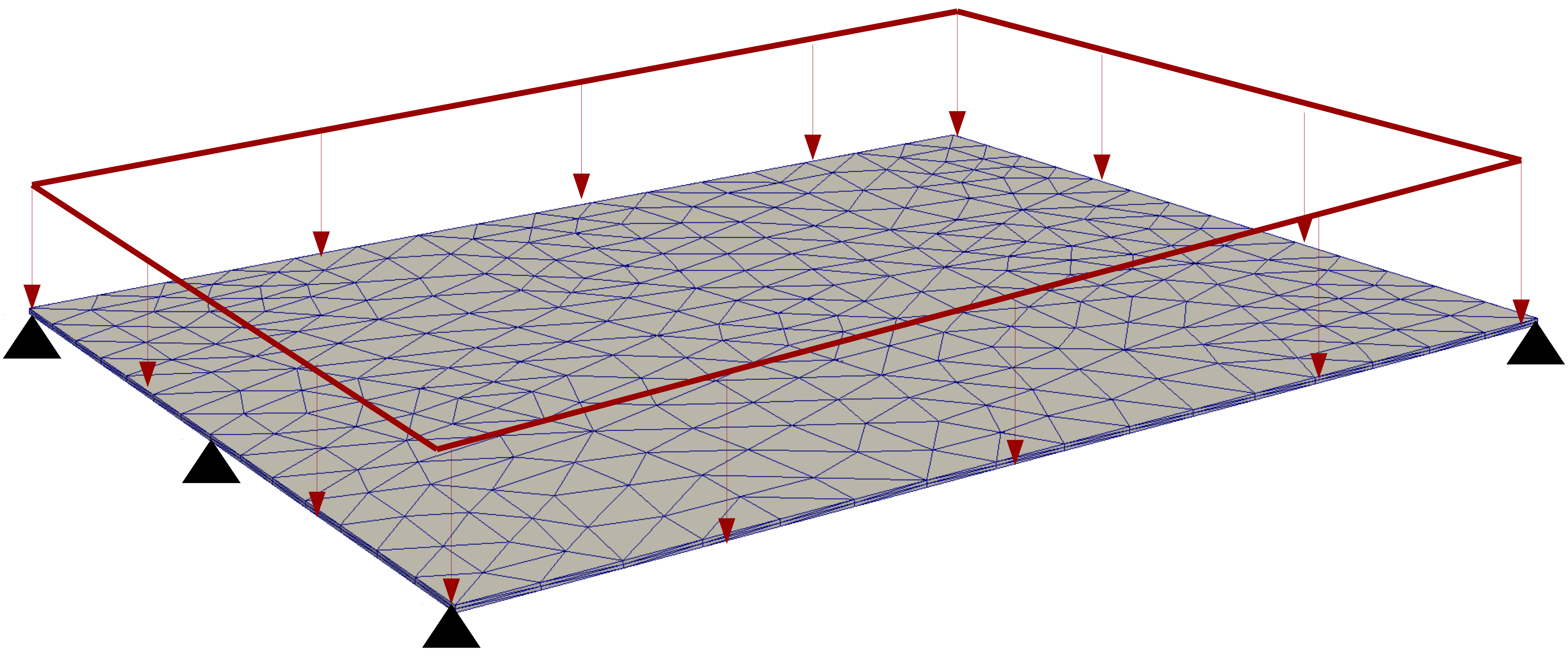

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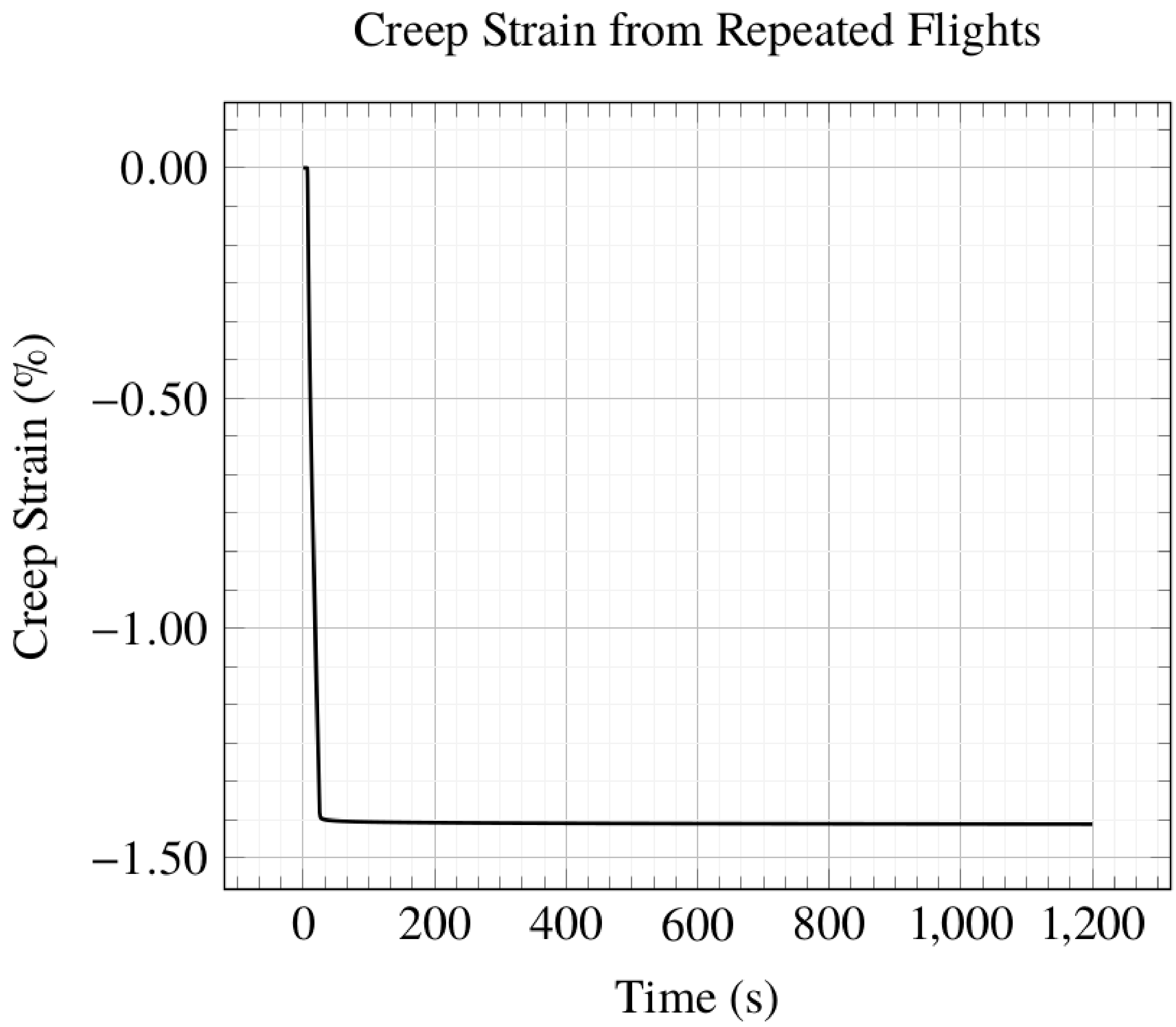
Results: 1D Analytical Bar

- Creep strain in bar: Maximum of 1.44%



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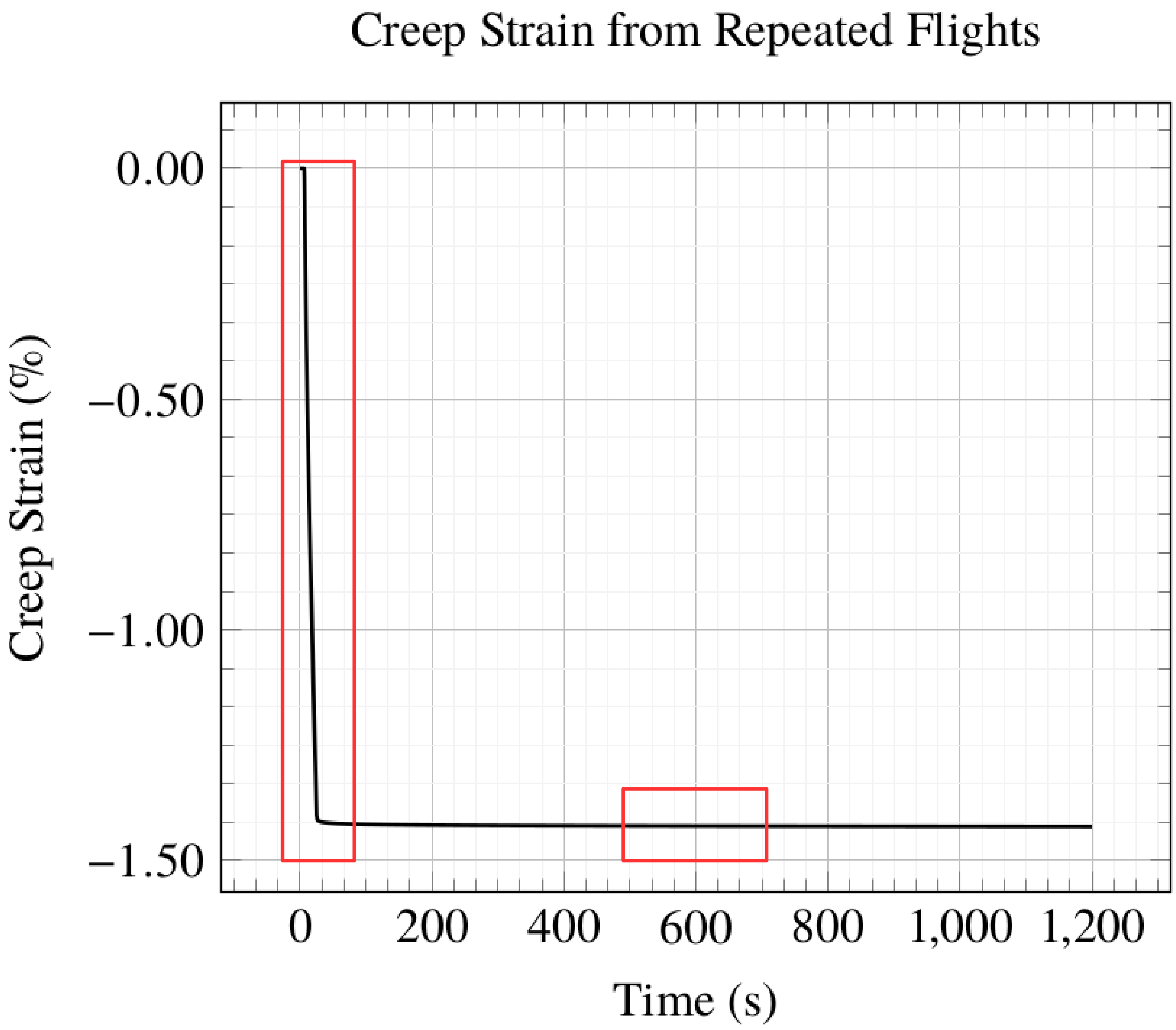

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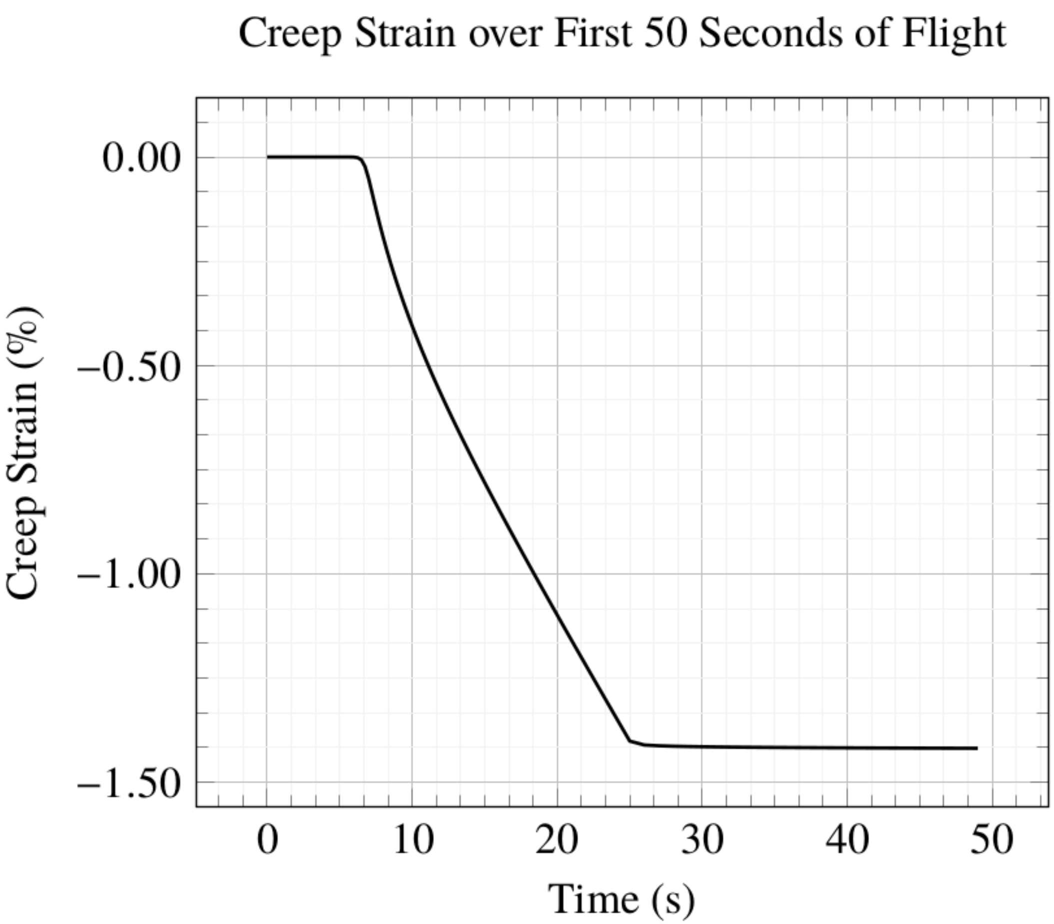
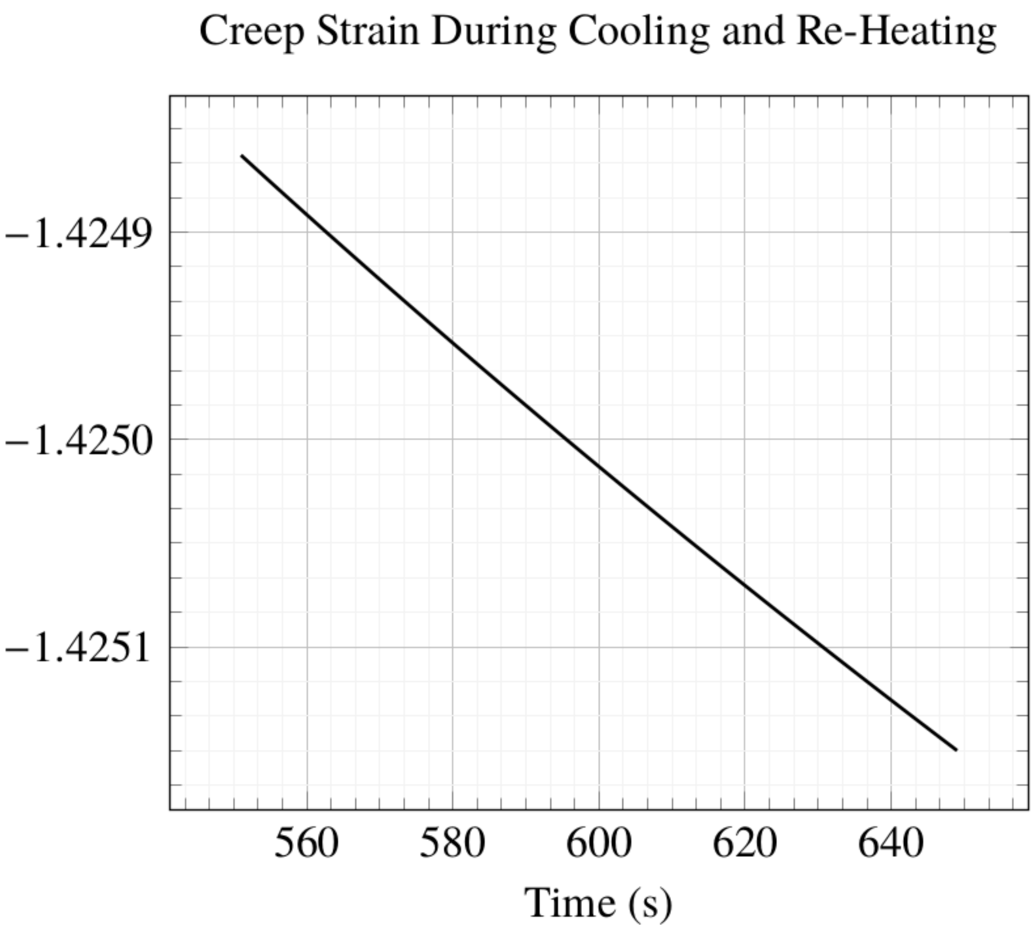
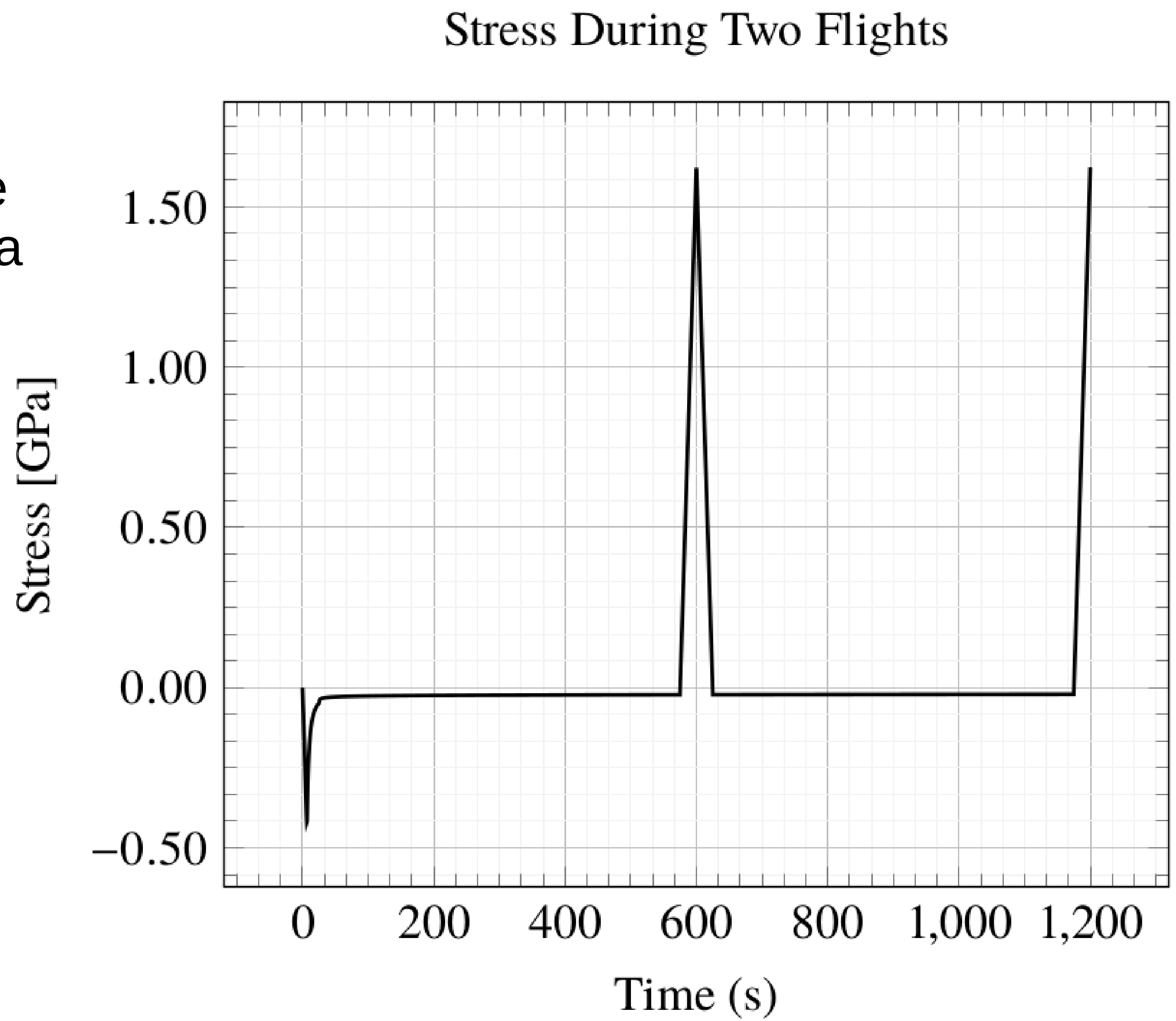




Results: 1D Analytical Bar

- Stress in bar: Maximum of 1.62 GPa
- Yield Strength: 1.1 GPa
- Creep reference stress: 22.7 MPa



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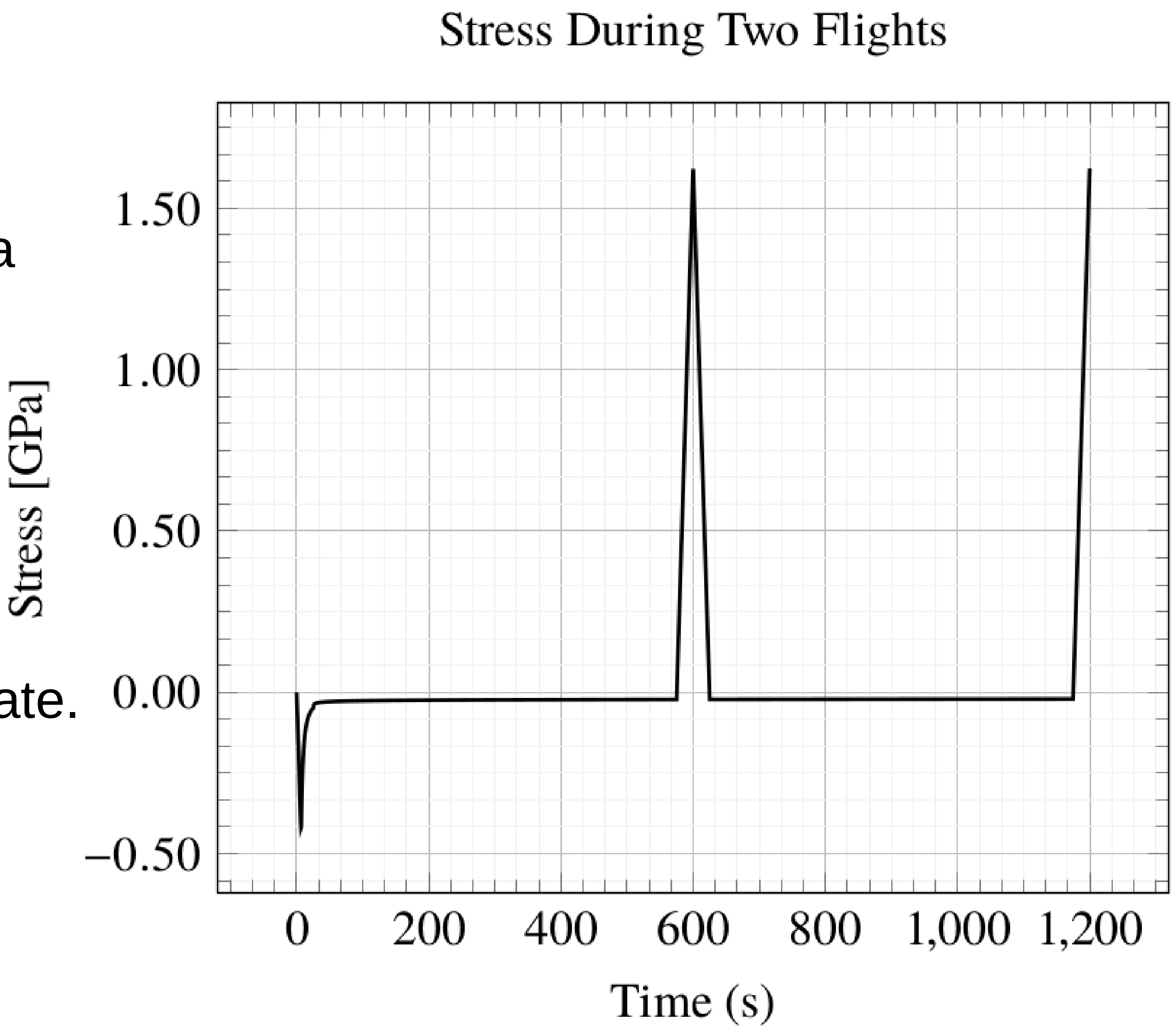
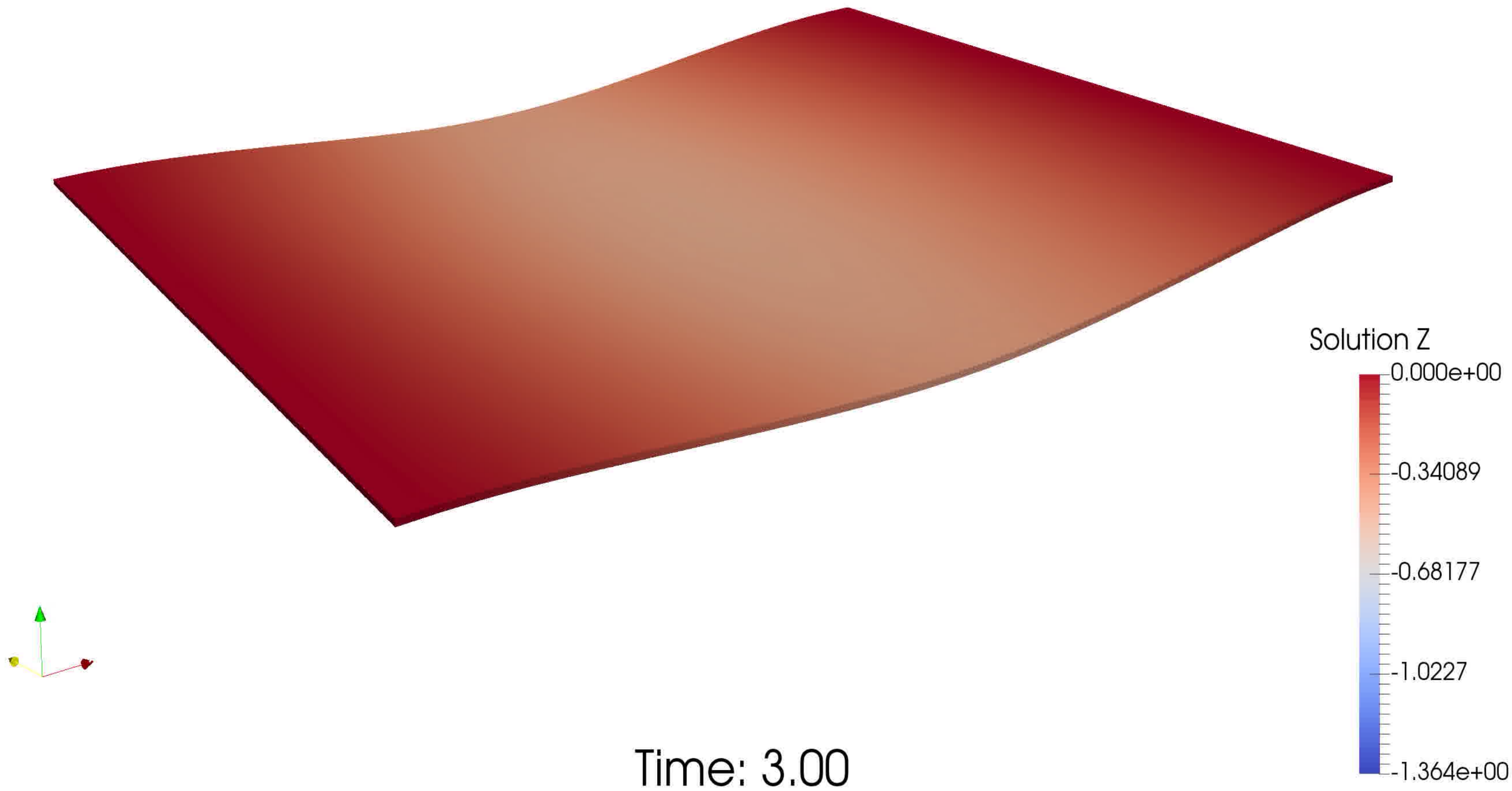
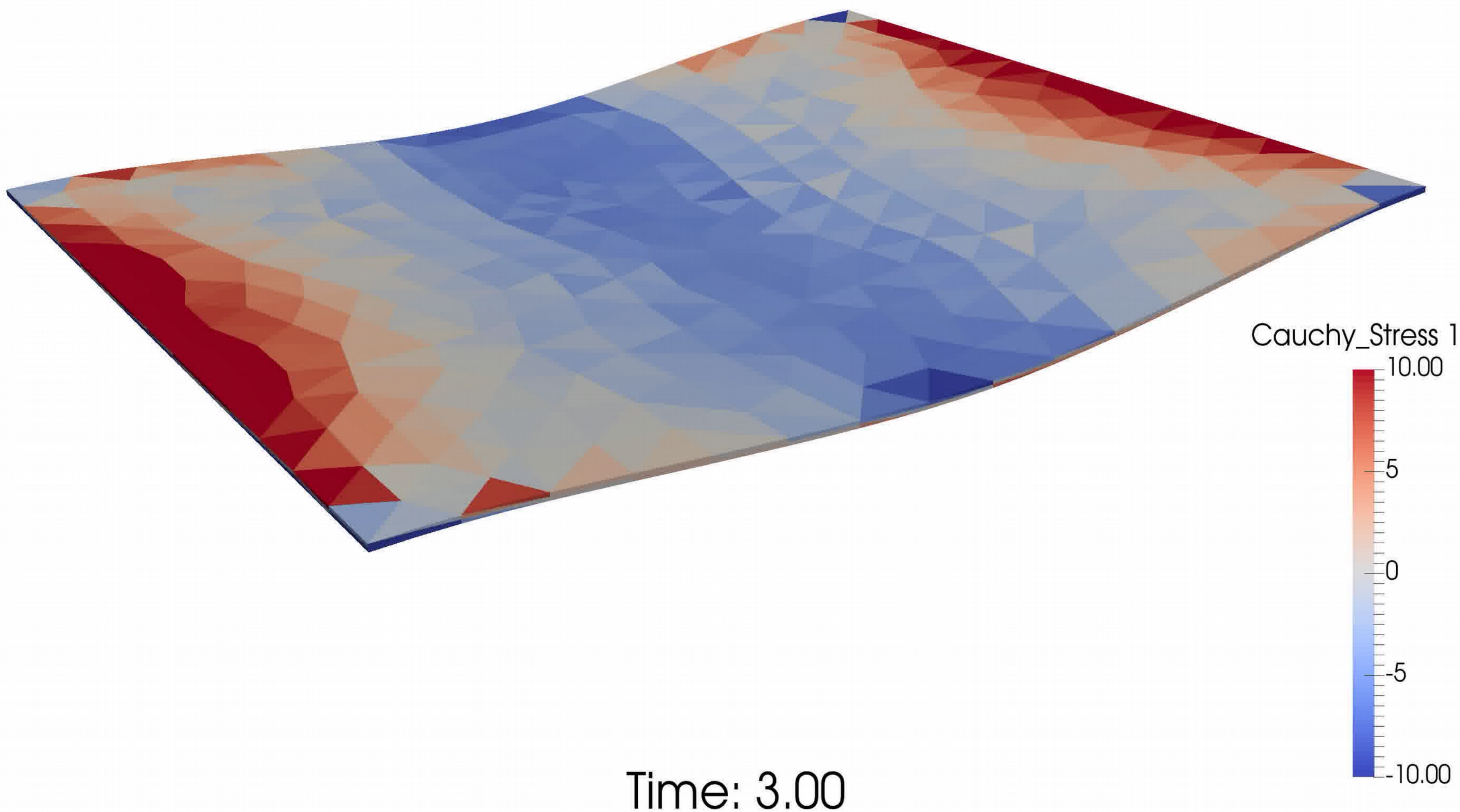


* Repeated with slower heating rate. Details in [11].

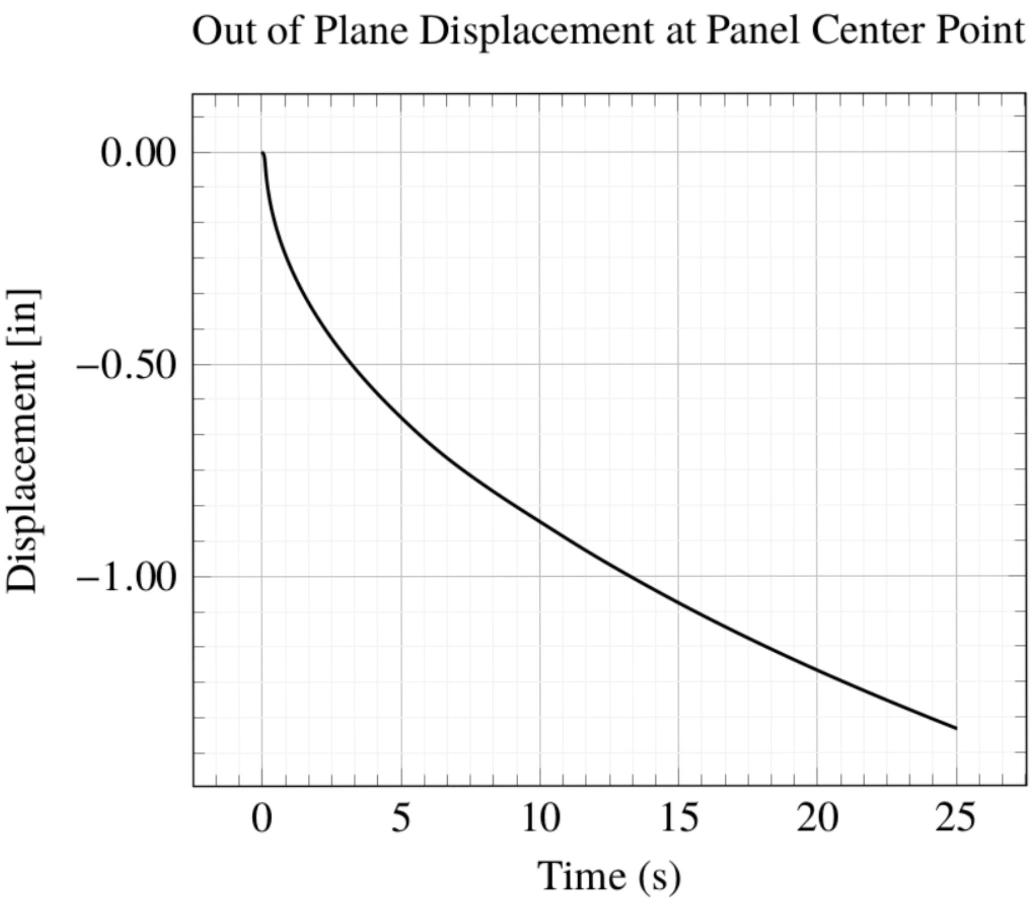
Results: Panel Displacement

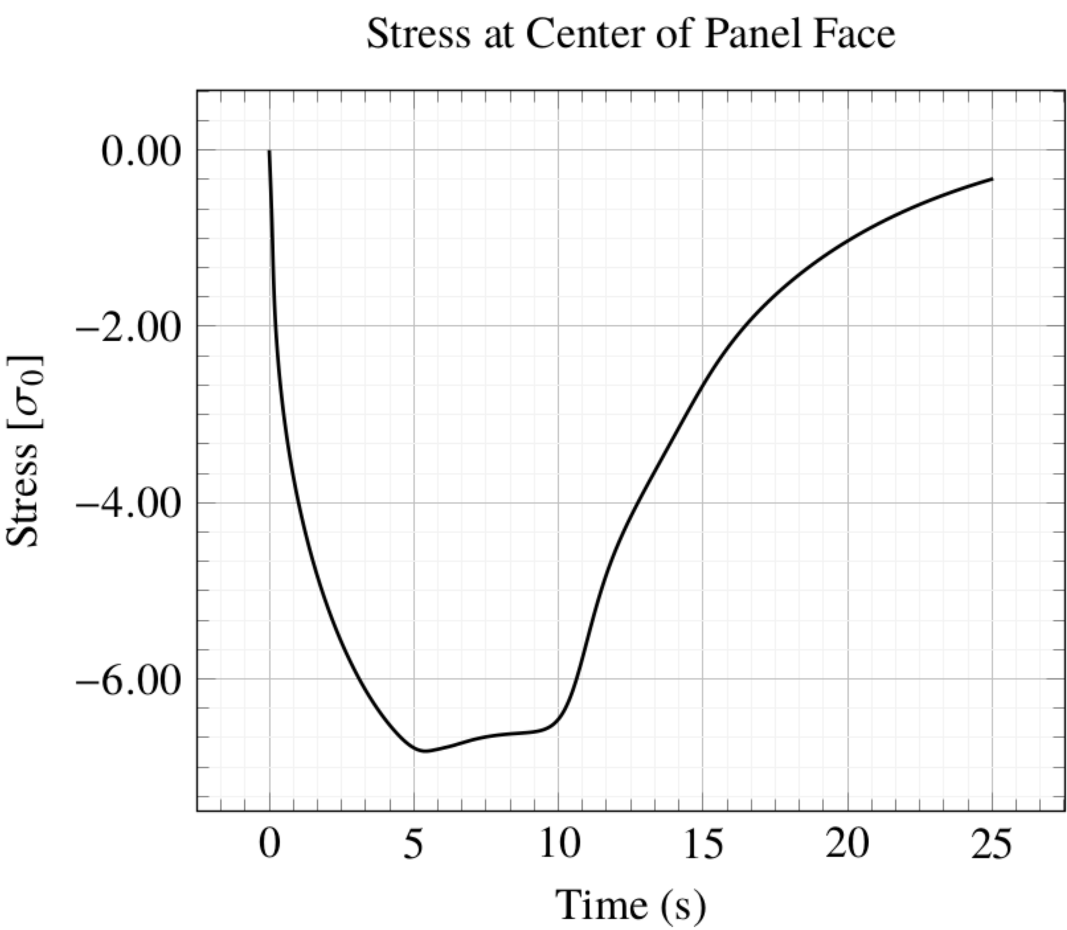


Results: Panel Stress



Results: Panel Center Point





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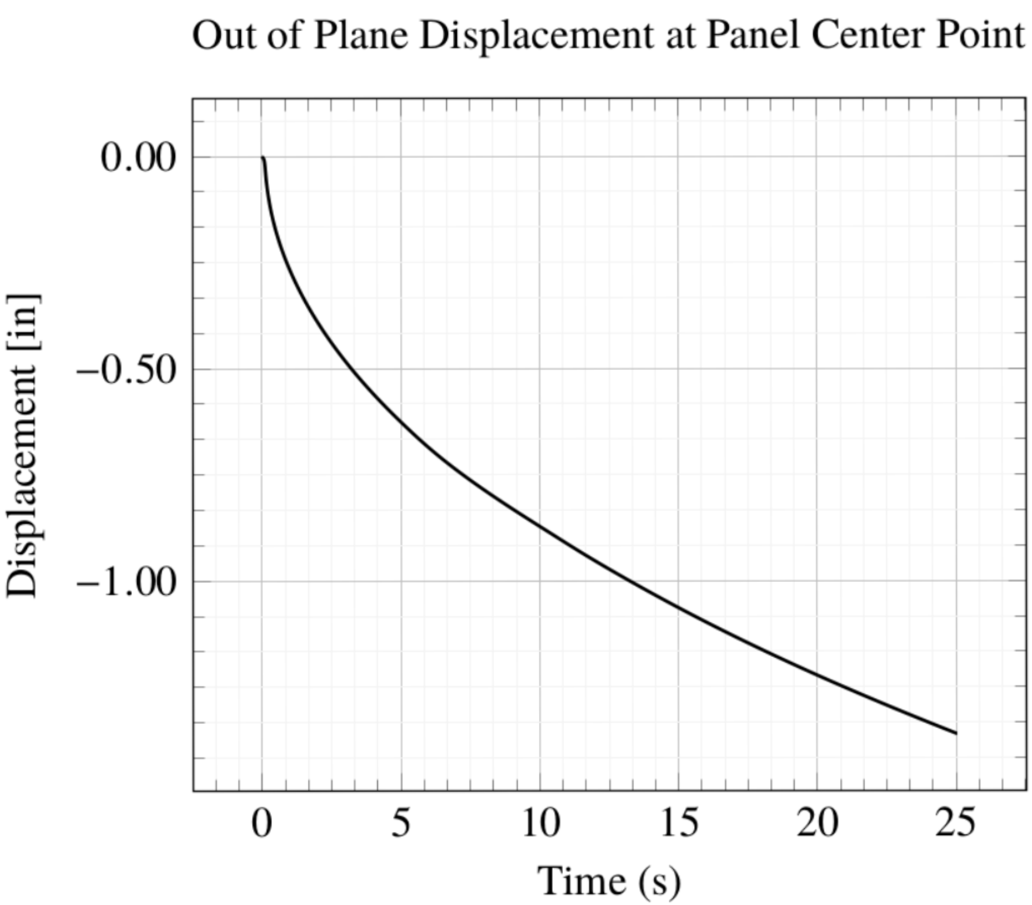
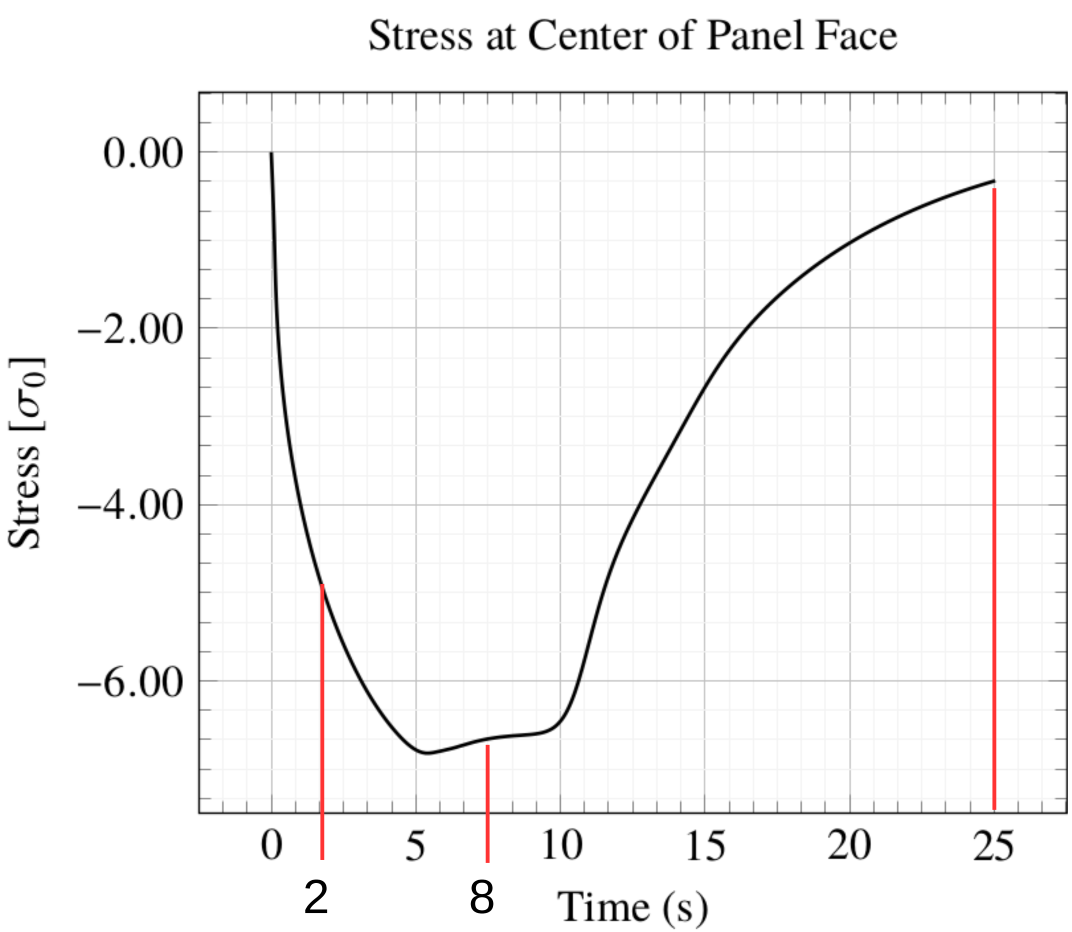
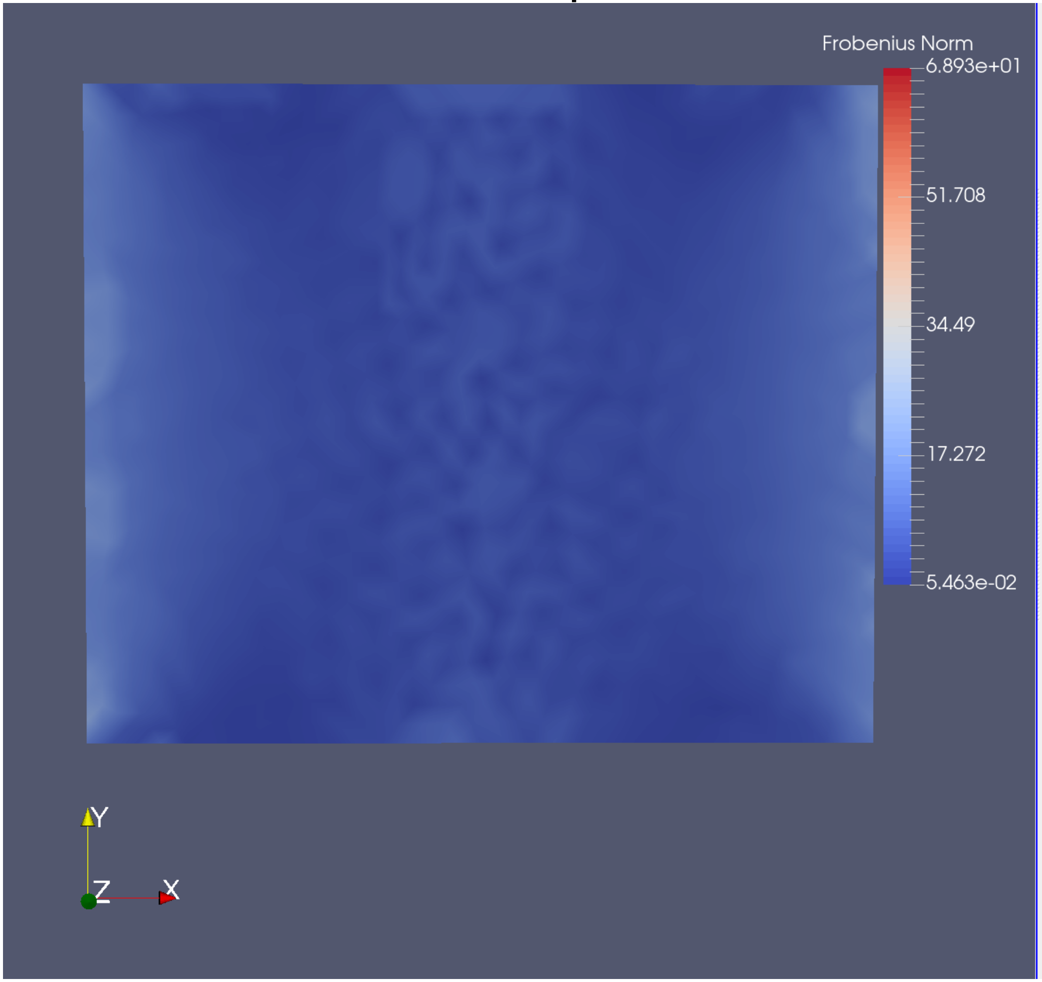




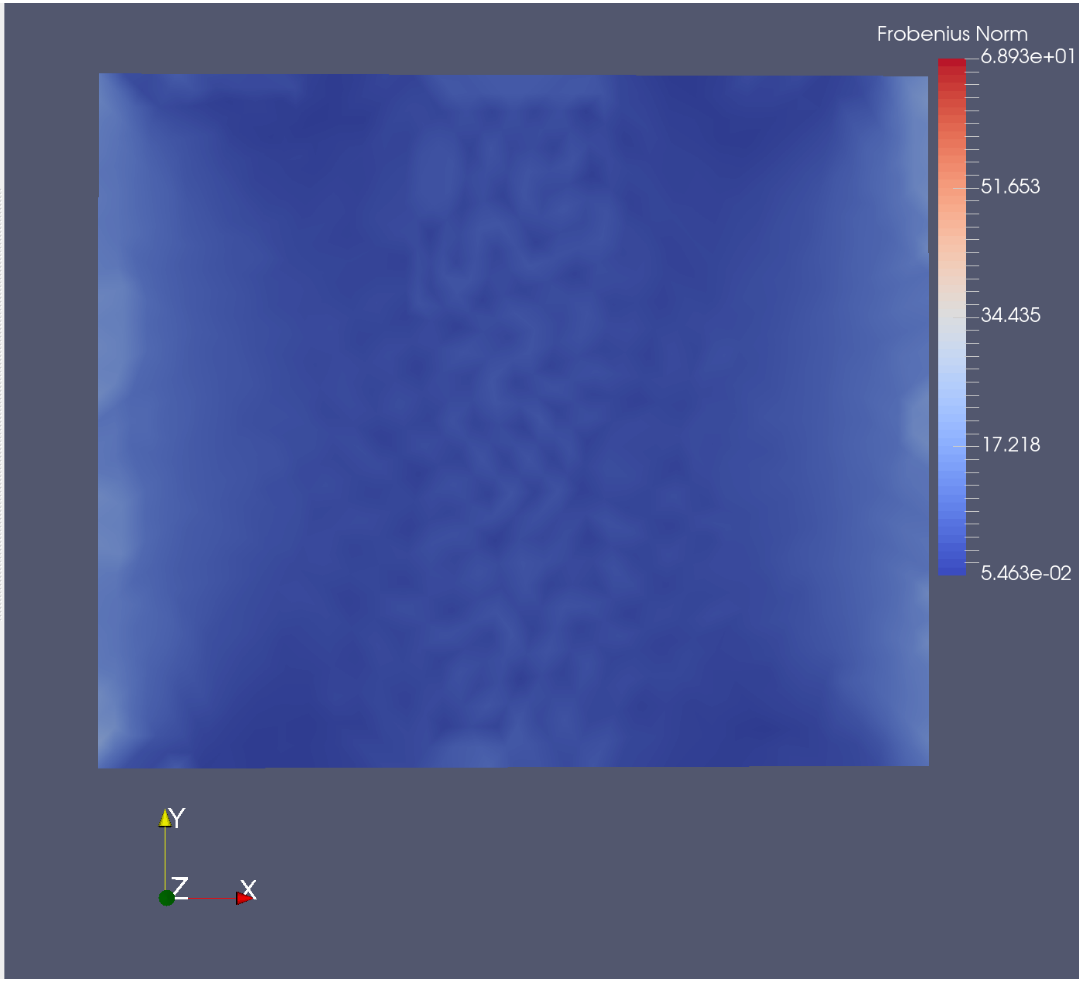
Results: With/Without Creep t=2s

Frobenius Norm

With Creep



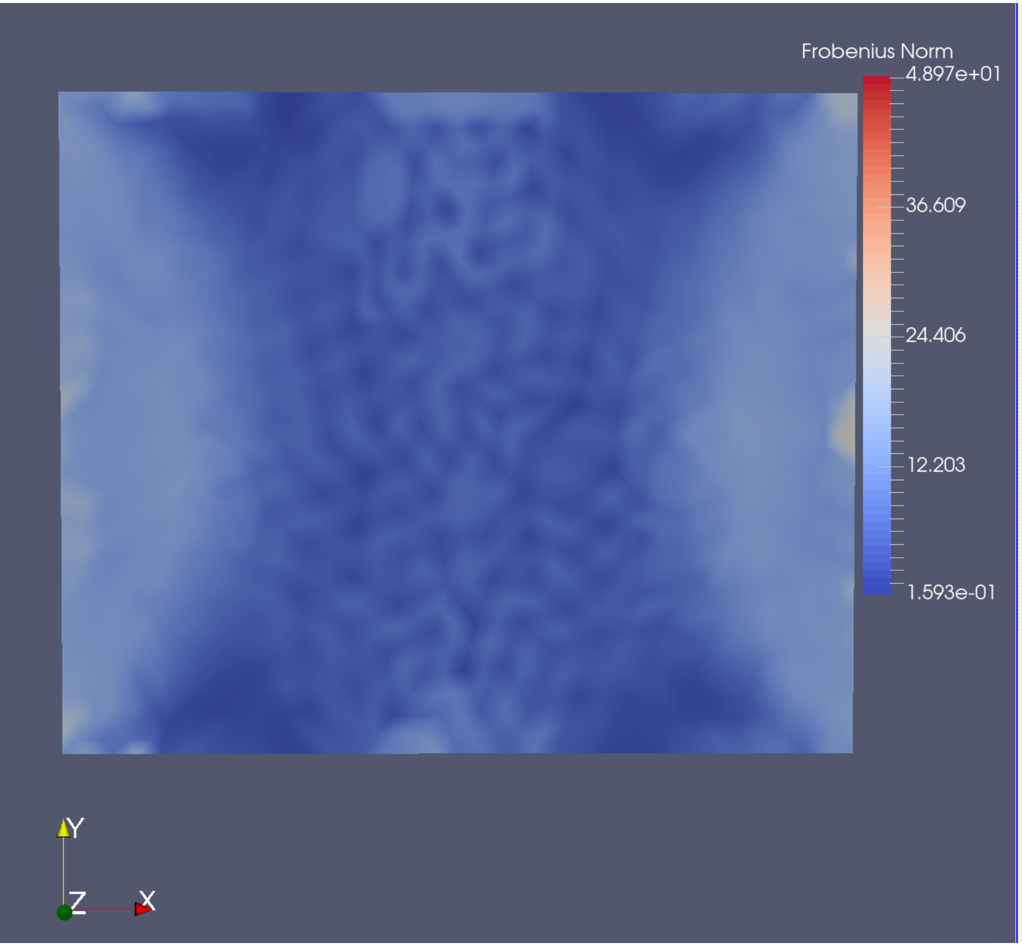
Without Creep



Results: With/Without Creep t=8s

Frobenius Norm

With Creep



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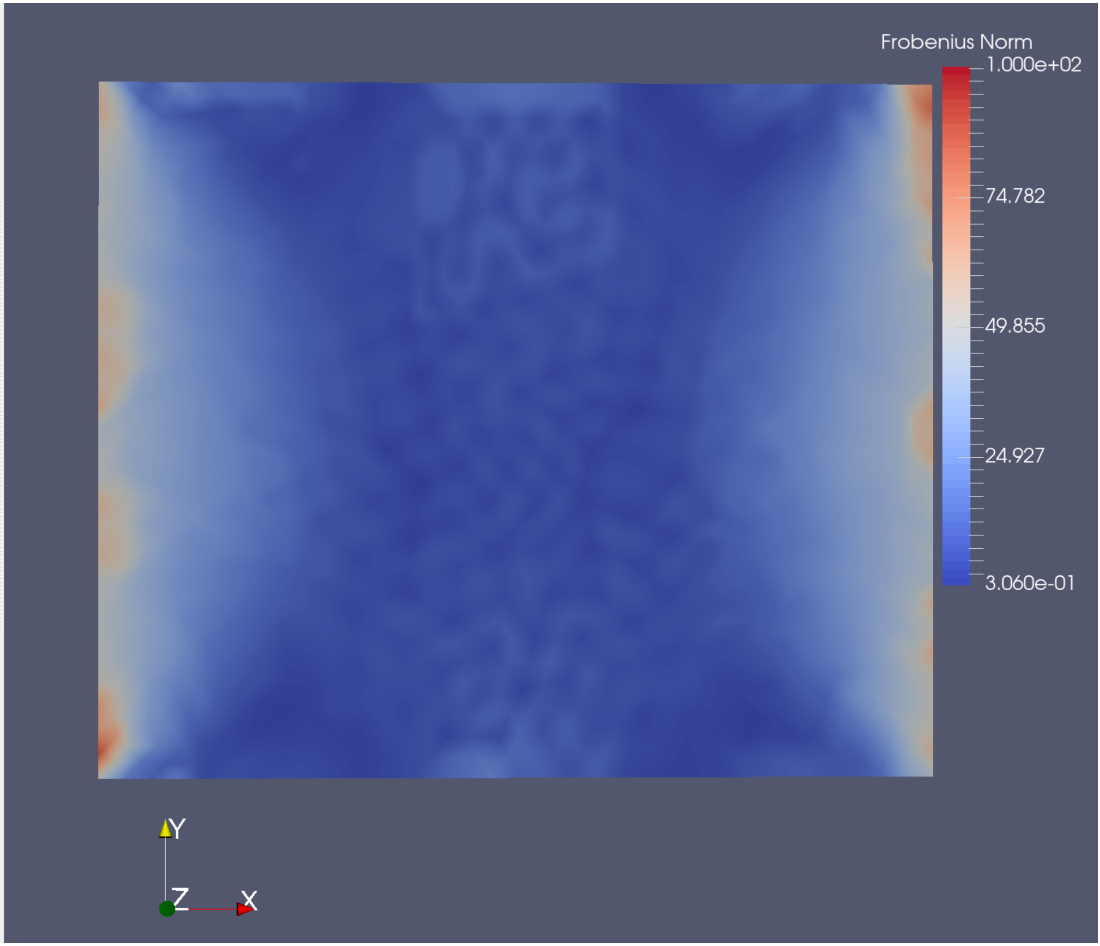
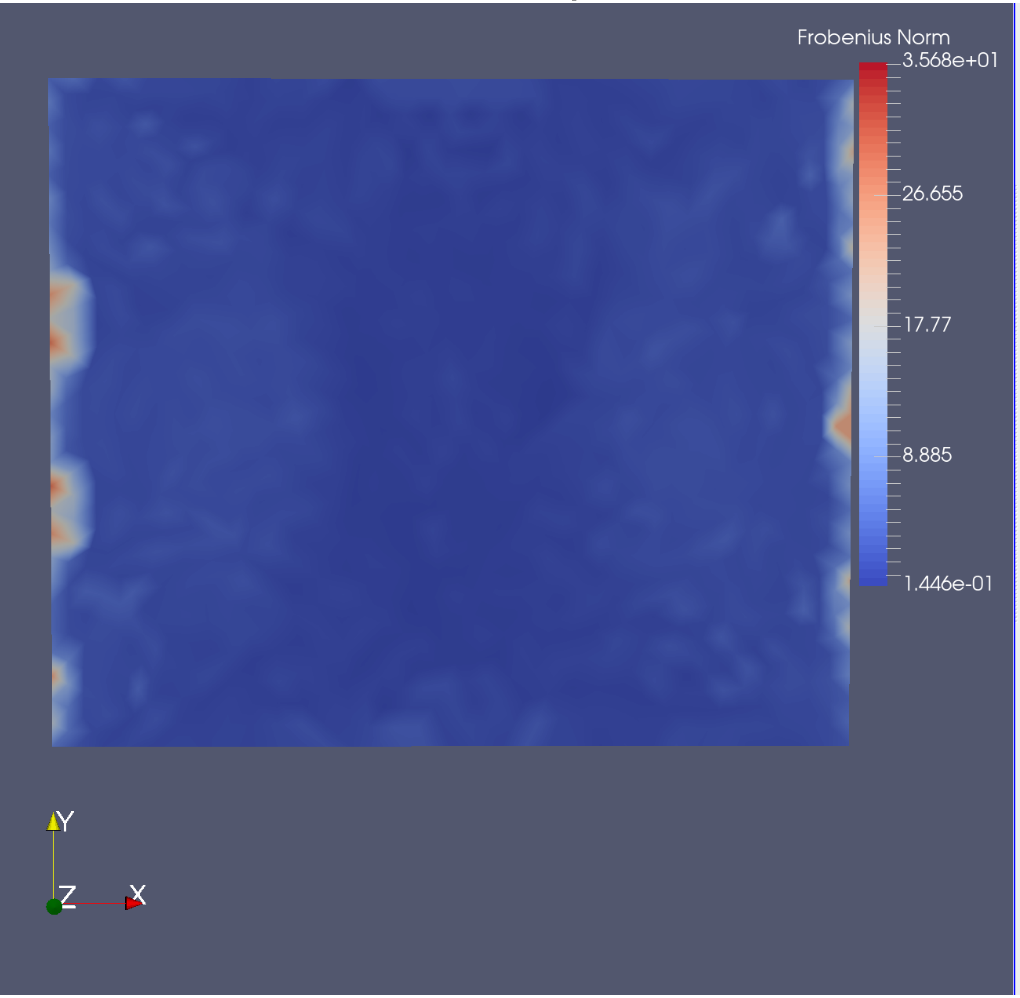


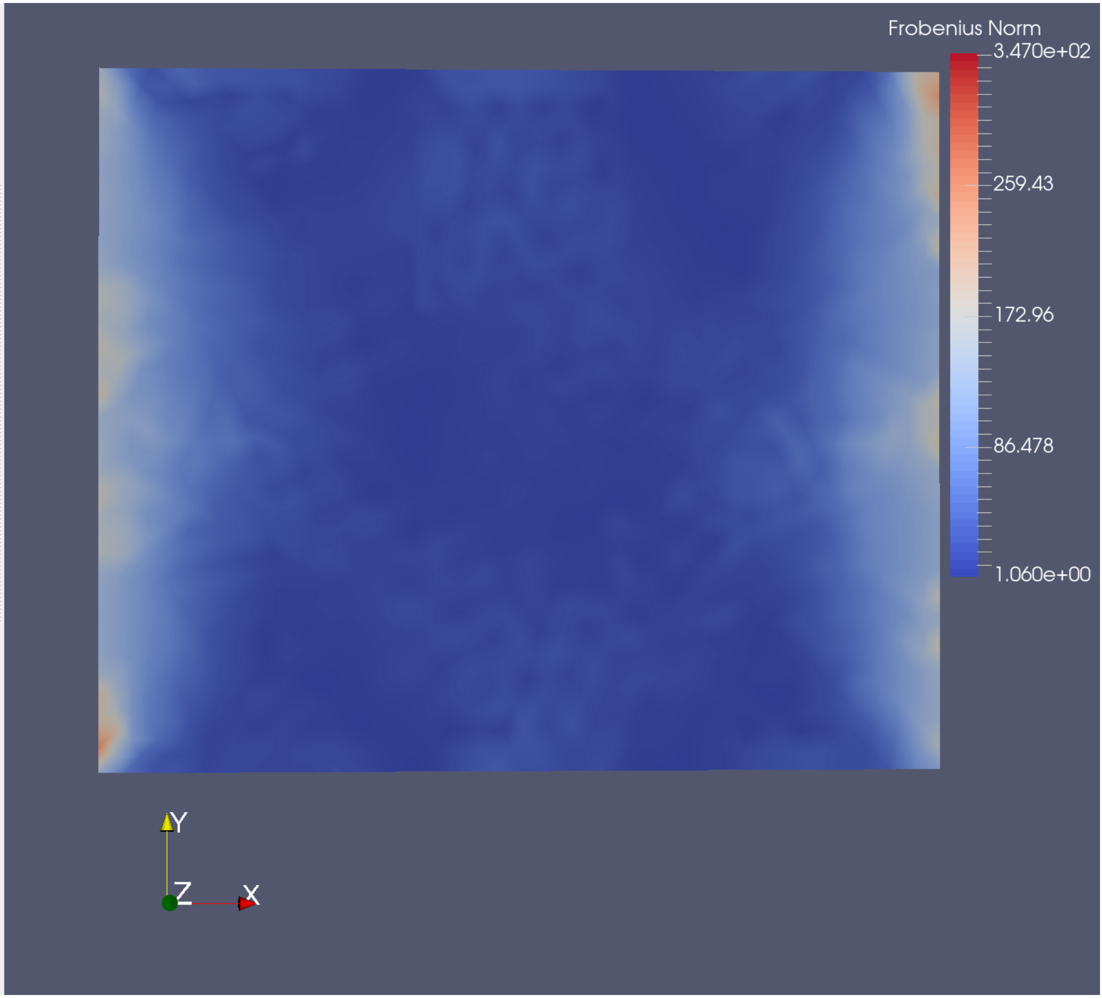
Results: With/Without Creep t=25s

Frobenius Norm

With Creep



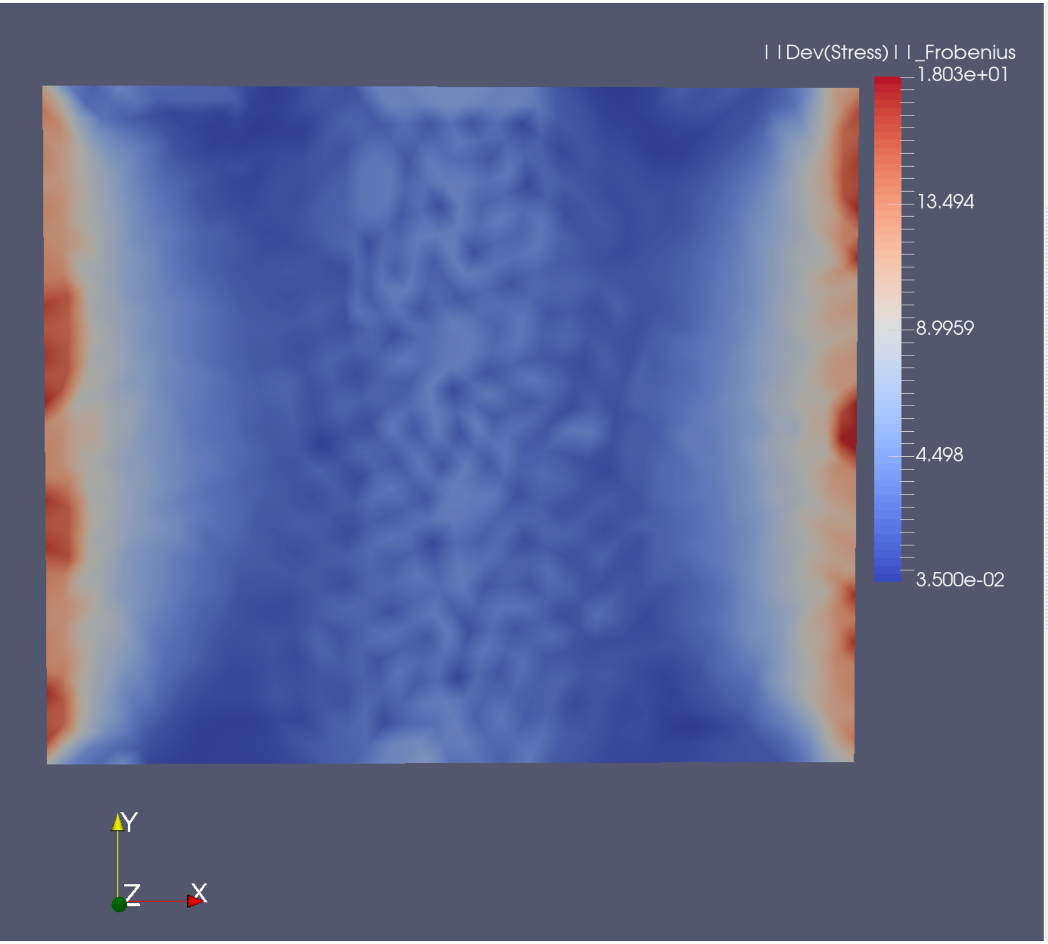
Without Creep



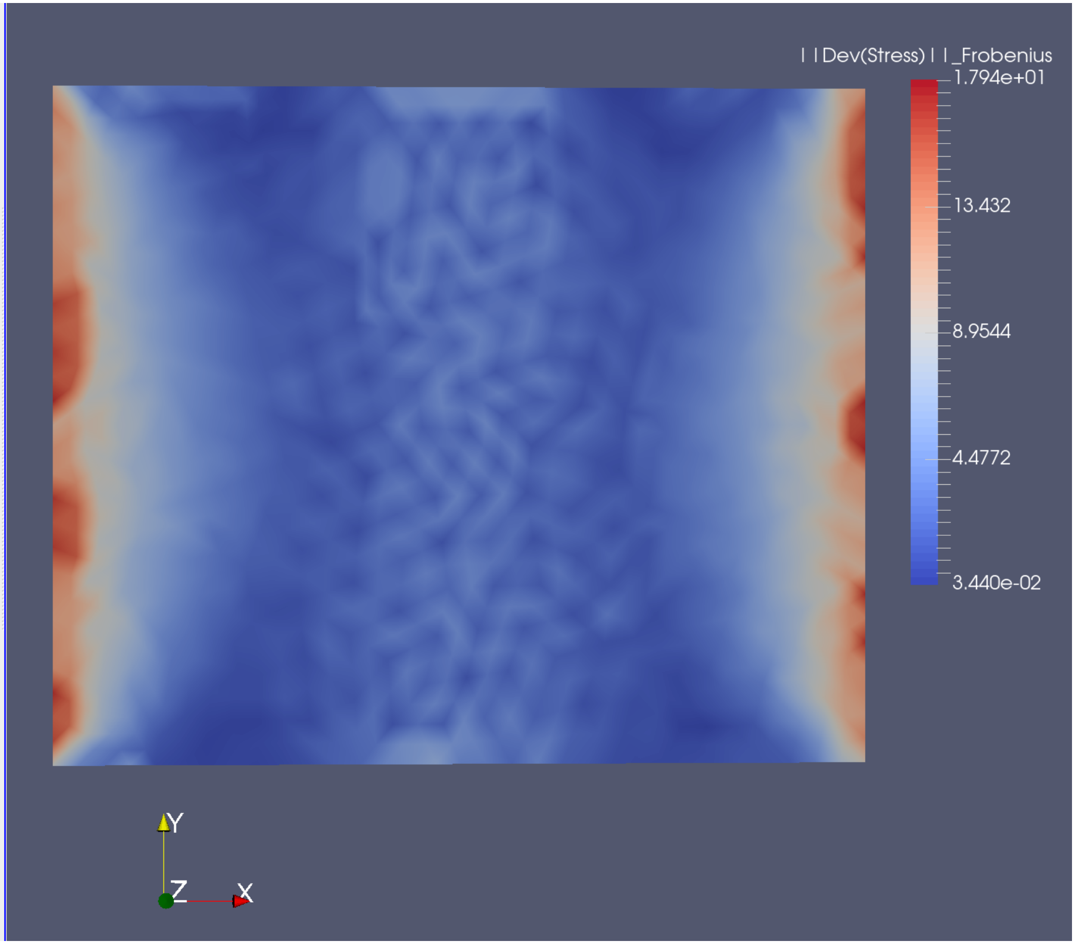
Results: With/Without Creep t=2s

Frobenius Norm of dev(Stress)

With Creep



Without Creep



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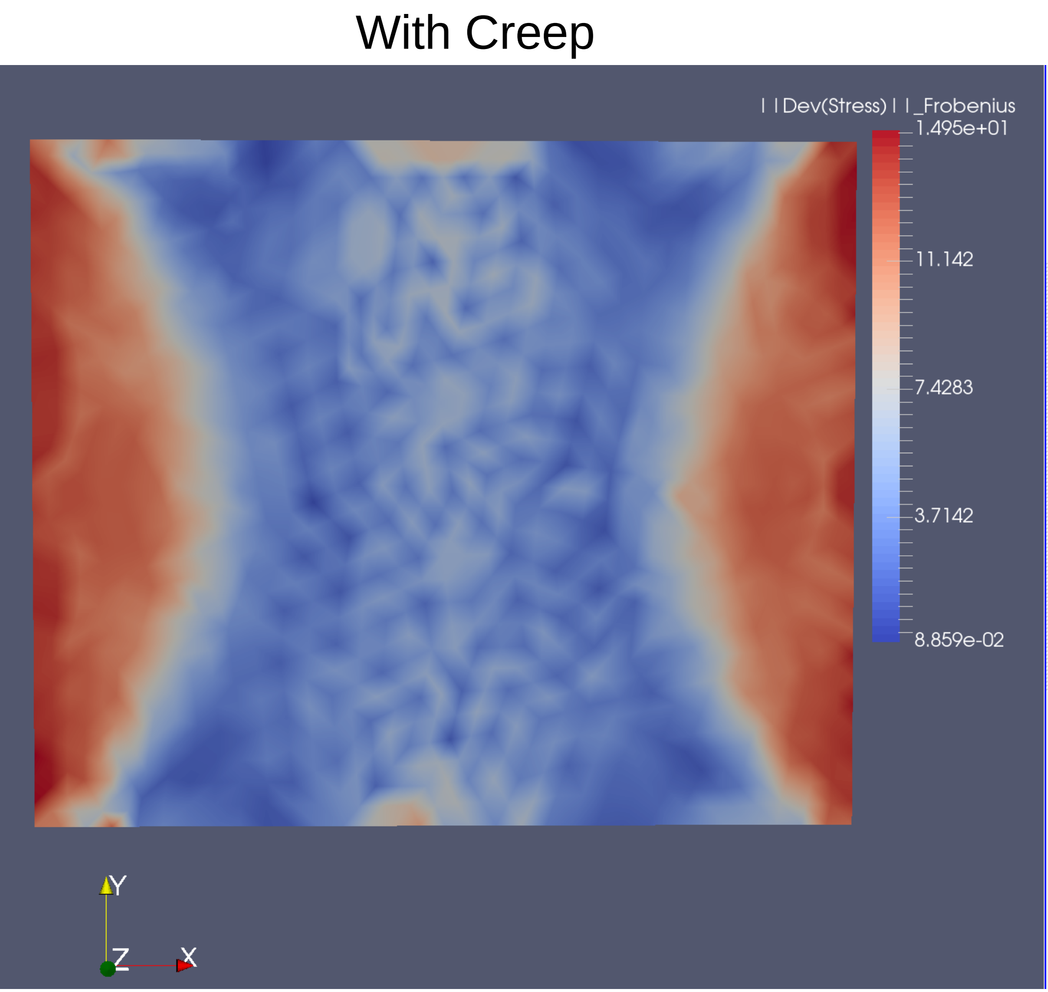

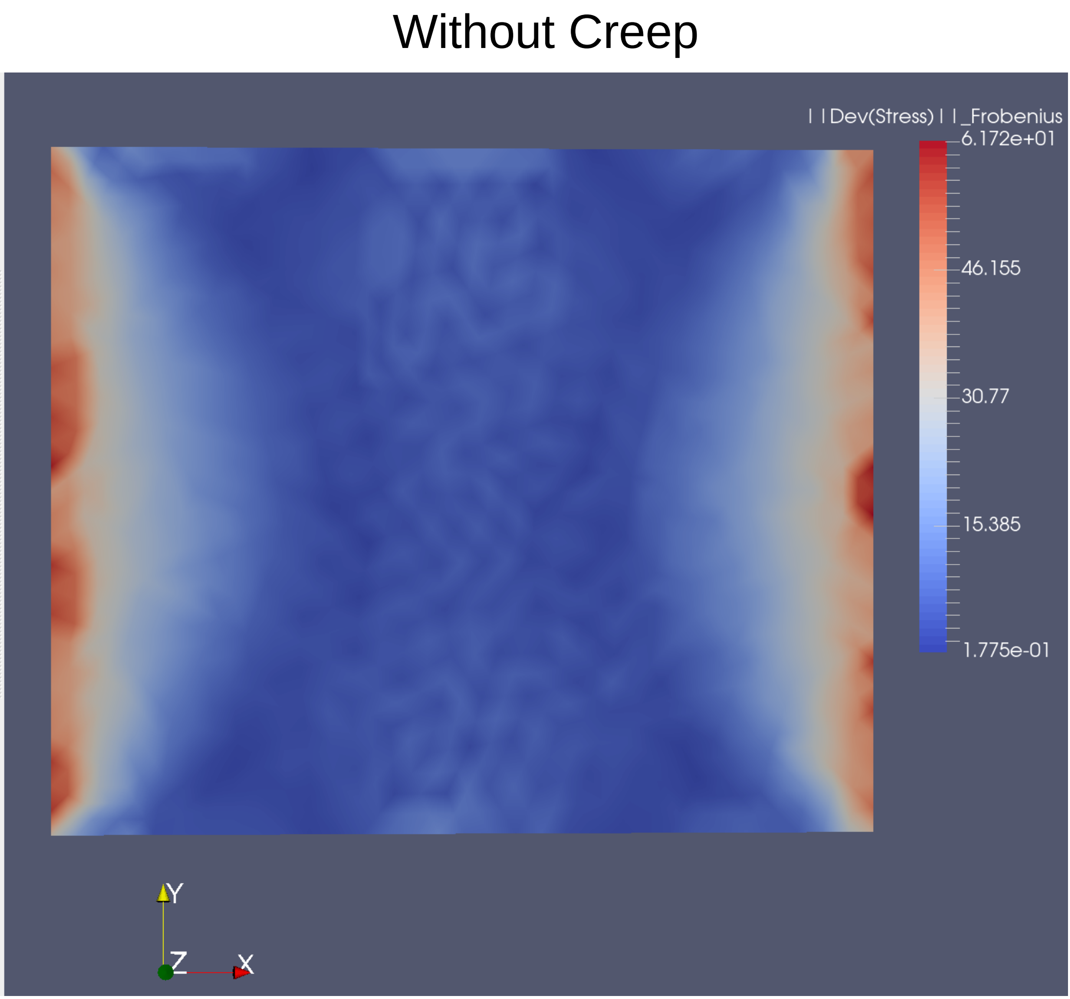

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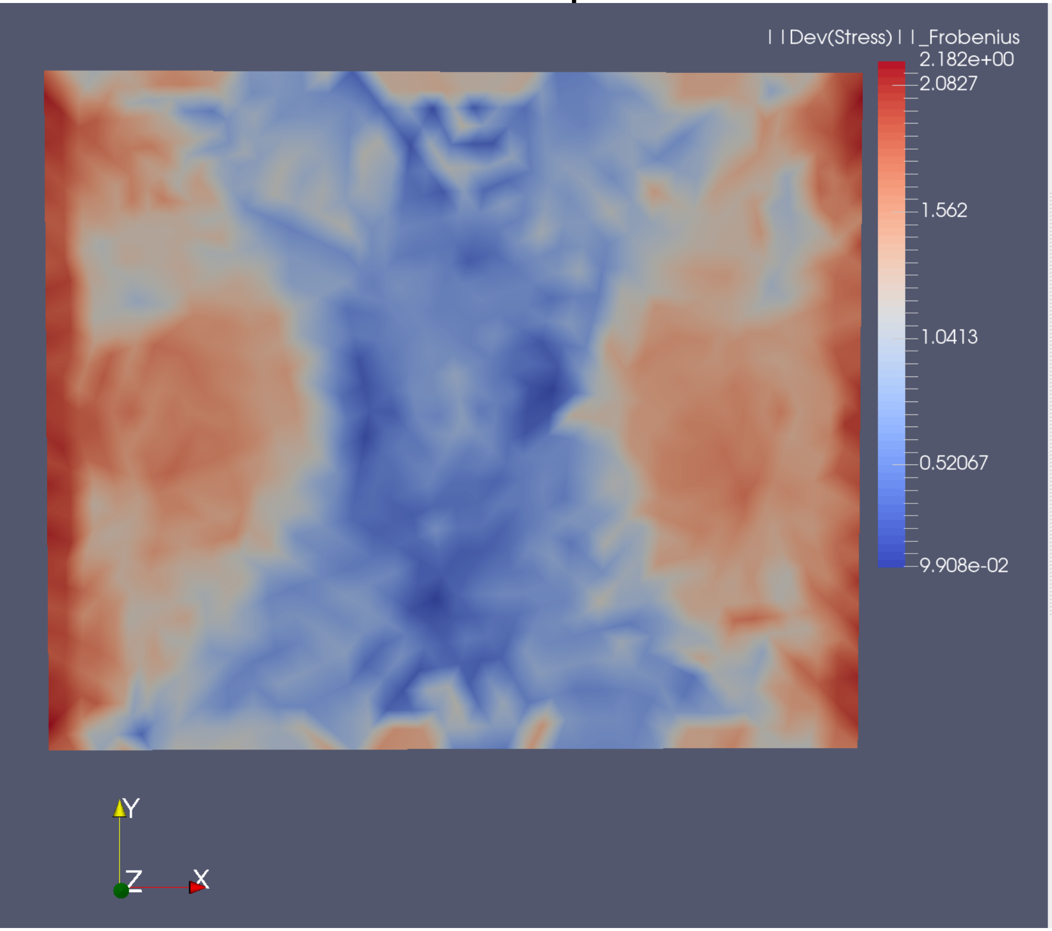

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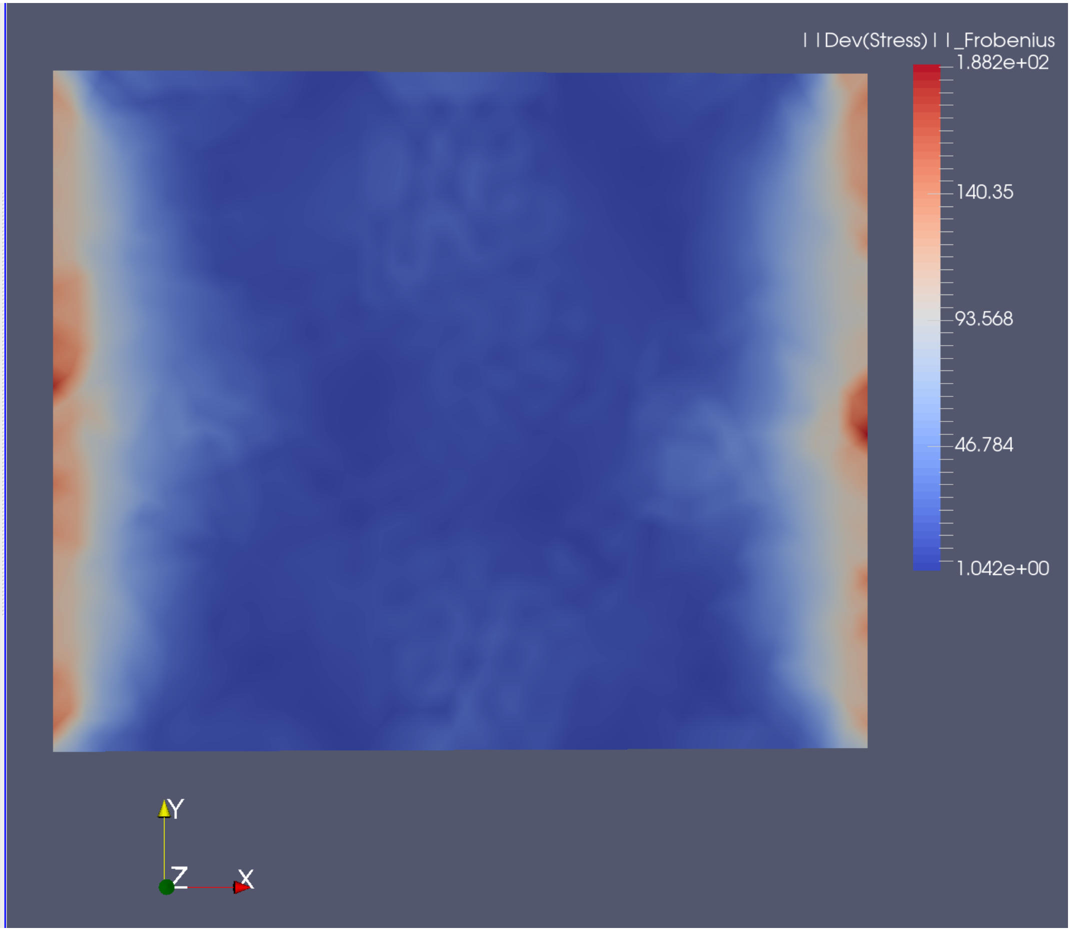

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Closing Remarks

- High speed vehicle structures must endure high temperatures

- 1D bar shows:
  1) Creep is activate for typical flight temperatures and materials
  2) Large residual stresses present after cooling

- Panel confirms creep activity for realistic geometry

- Can expect inelastic strains and residual stresses in panel after cooling

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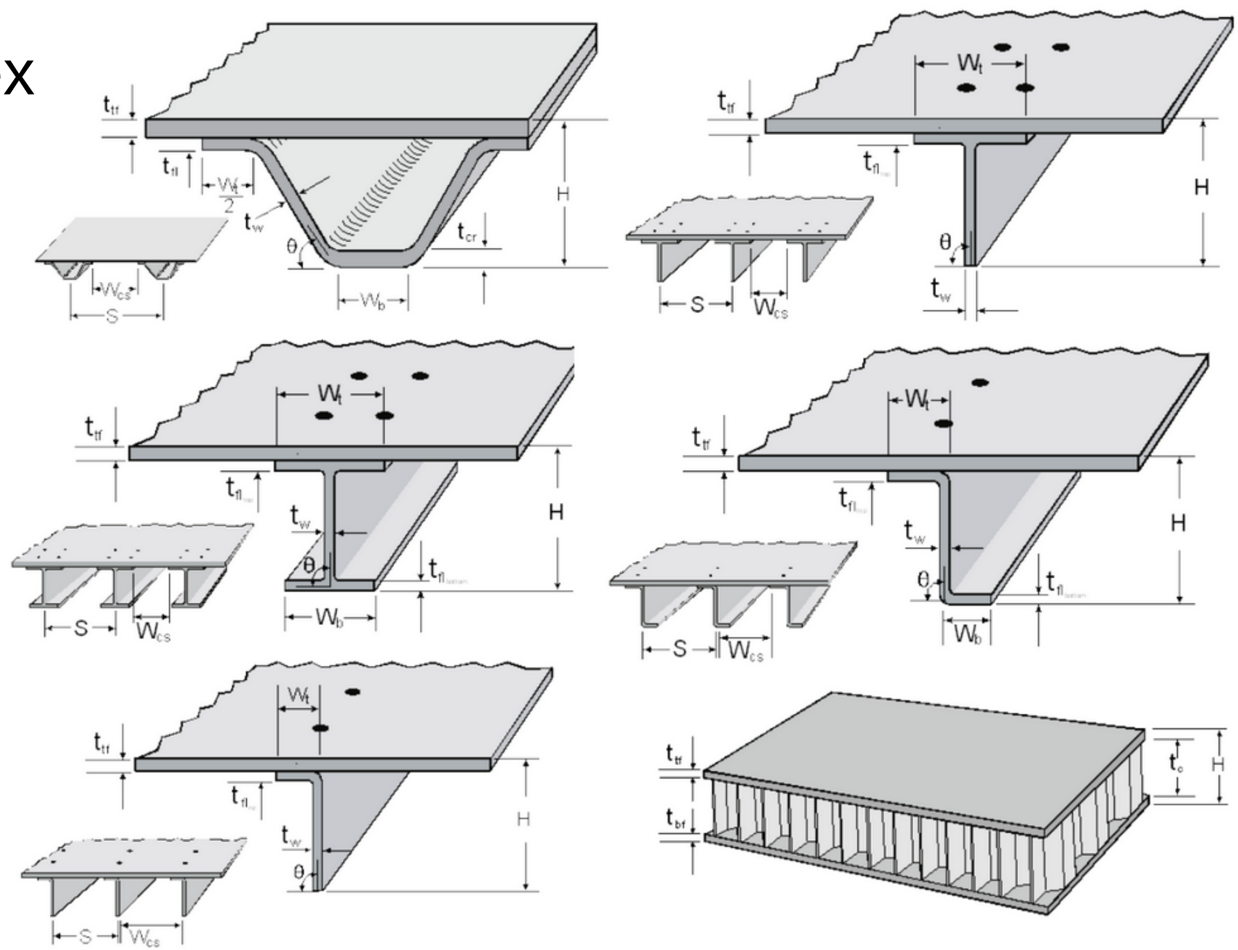
Future Work

- Modeling more complex shapes
  - Including stiffeners and supporting structure
- Adding von Mises plasticity
- Including cruise and cooling phases
  - Multiple cycles for multiple flights



Panel design options.
Image from [10].

Question & Comments

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USC Viterbi School of Engineering

AFRL THE AIR FORCE RESEARCH LABORATORY
LEAD I DISCOVER I DEVELOP I DELIVER

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