Viscous Deformation of a Fused Quartz Tube Caused by Furnace Malfunction: Modeling and Analysis

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Final Project

Sunny Sue Wicks
Stephen Alan Steiner III
Massachusetts Institute of Technology

Introduction

- Electric clamshell or “tube” furnaces are commonly used in materials science labs for chemical vapor deposition, annealing
- Furnaces typically have three independently-controllable electric heating coils or “zones” rated for 1200°C service
- A fused quartz tube is used often used to contain the process reaction

One Dark And Stormy Night at MIT…

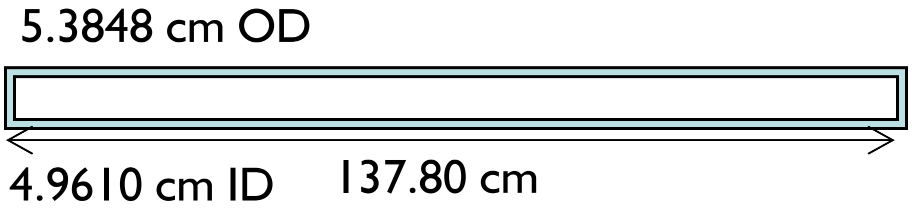
- An 1100°C process was being run when thermocouples in Zones 1 and 2 broke - apparently a thermocouple was in direct contact with a heating coil
- The temperature controller went to full duty cycle and Zone 1 went on thermal runaway (1200°C or greater)
- Zones 2 and 3 remained on but it's not certain how hot
- After four hours or so, the fused quartz tube was found draping out of the left side of the furnace

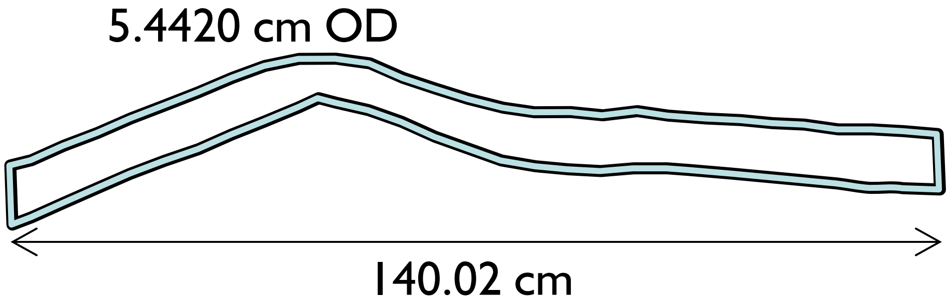
Before process

After process

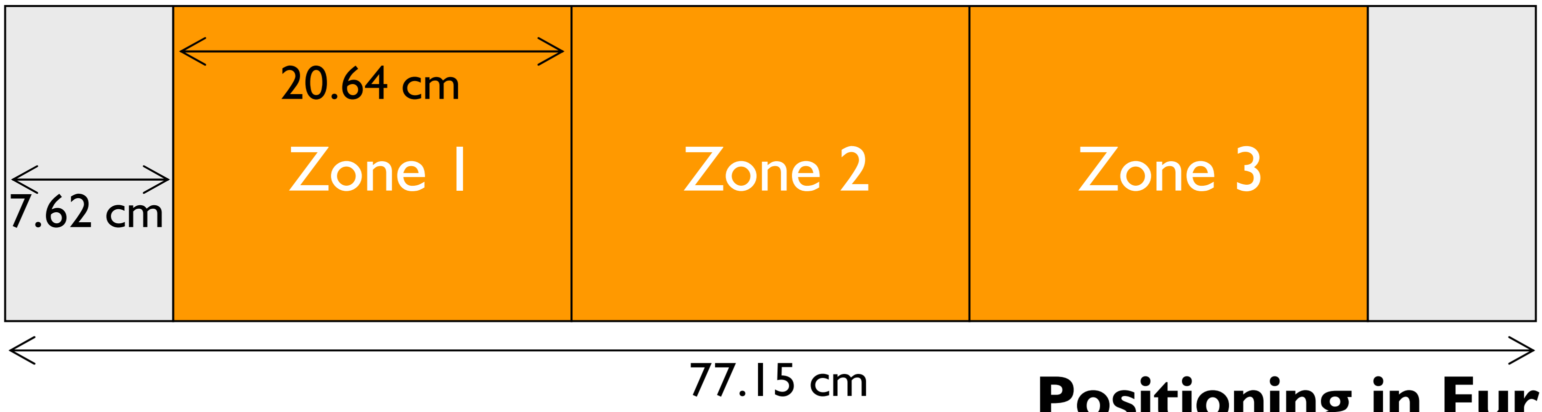
Actual Measurements

Material is fused quartz

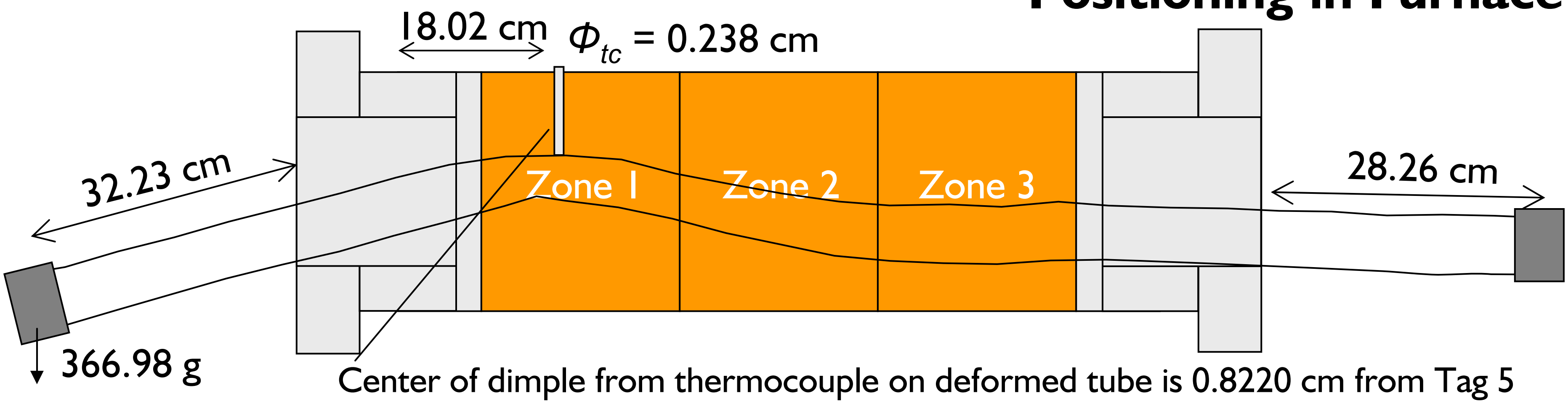




Furnace Dimensions

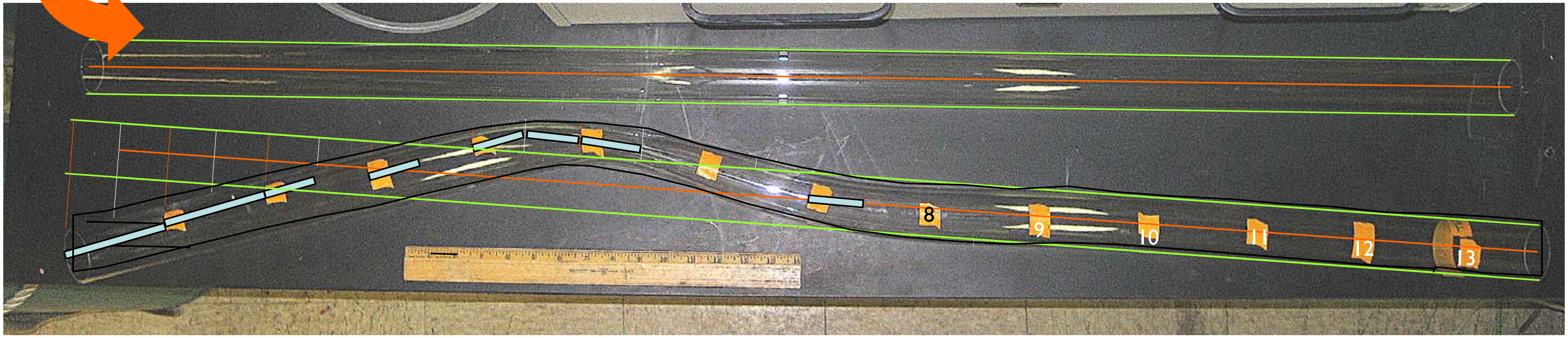


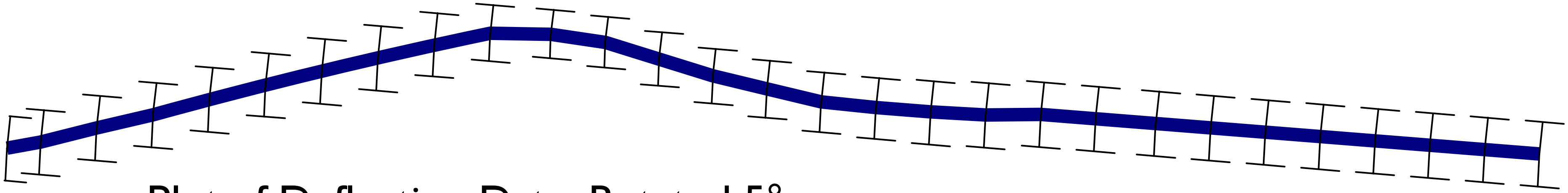
Positioning in Furnace



Relative Deflection Measurements

Image analysis was used to determine deflections relative to a new fused quartz tube



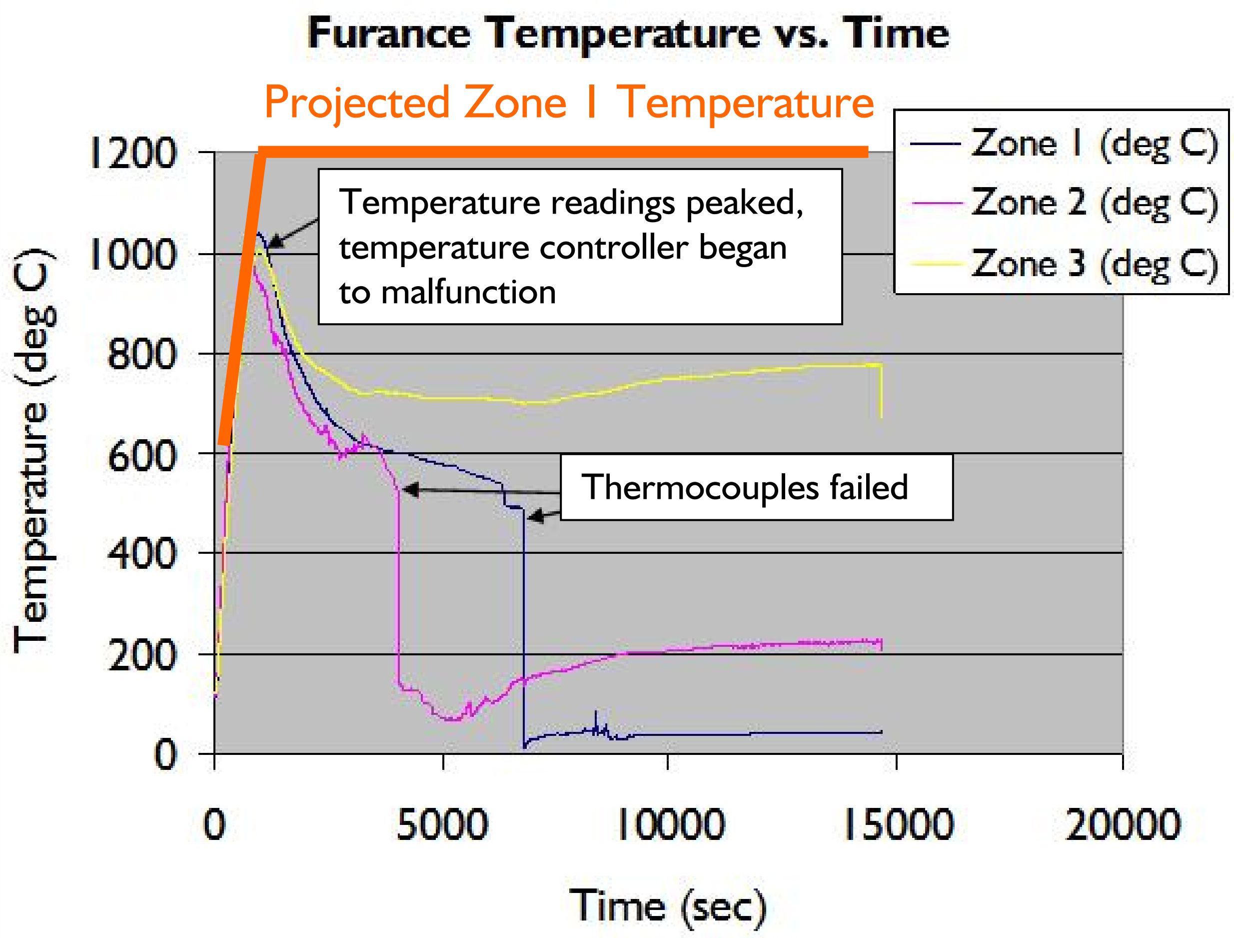


Plot of Deflection Data, Rotated 5°

Questions

- What temperature did Zone 1 likely reach?
- How and why did the fused quartz tube deform the way it did?
- Why did the tube cross section pinch near the point where it inflected?

Temperature Profile

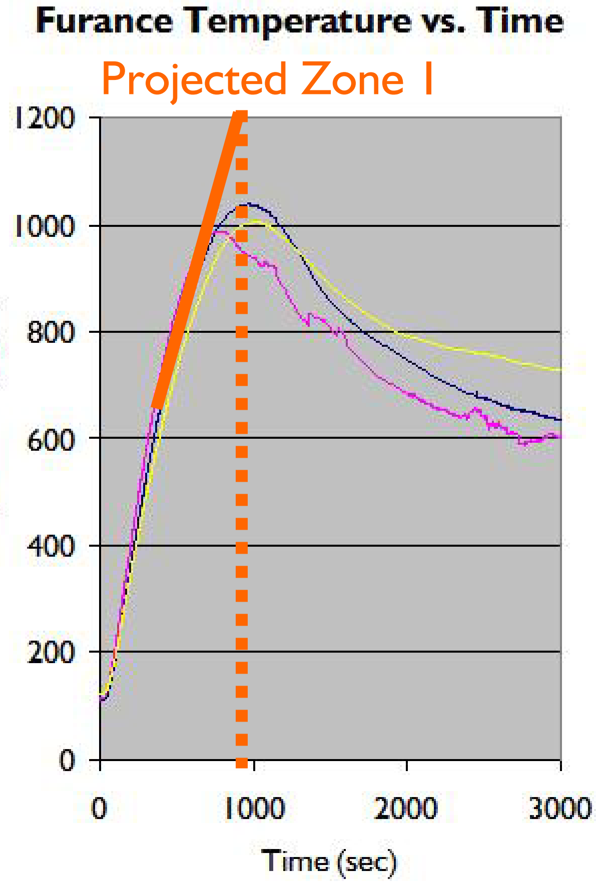


Furance Temperature vs. Time

Projected Zone 1 Temperature

Temperature readings peaked, temperature controller began to malfunction

Thermocouples failed



Furance Temperature vs. Time

Projected Zone 1

Methodology

Analytical Model (Simple Beam Theory)

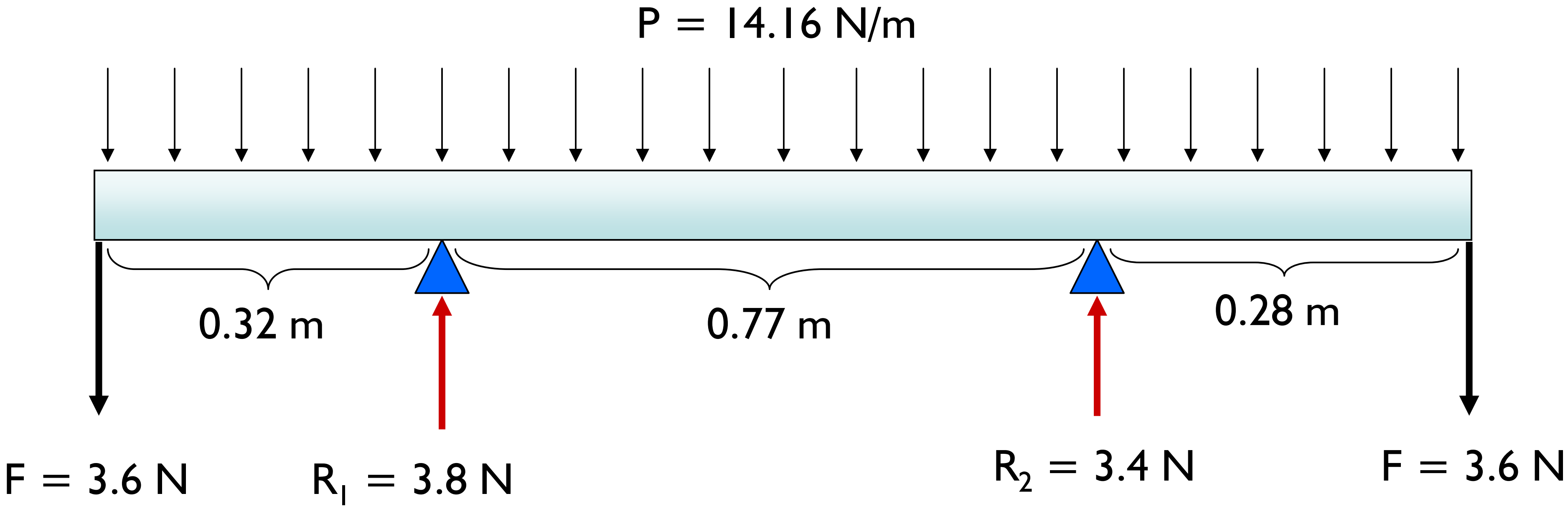
Finite Element Modeling (Two-Layer Viscoplastic Model in ABAQUS)

Empirical Analysis (Deflection Data, Shape Trends)

Simple Beam Theory Model: Assumptions

- Temperature is significantly below T_g so material is elastic and brittle
- Circular cross-section of the tube does not deform during bending
- Tube length is much greater than tube diameter
- Loading and deflection occur in vertical direction only
- Small deflections

Analytical Model: Derivations



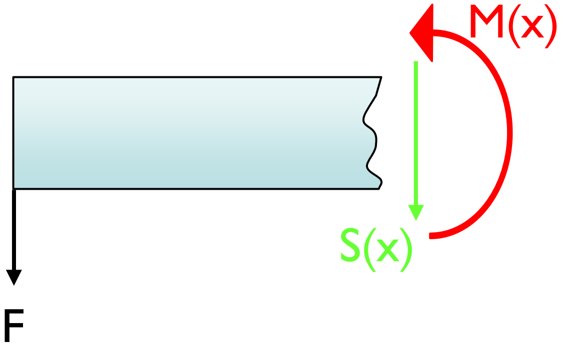
Simple Beam Theory

- Pinned in two locations
- Distributed load from weight of tube
- End loads from weight of aluminum endcaps

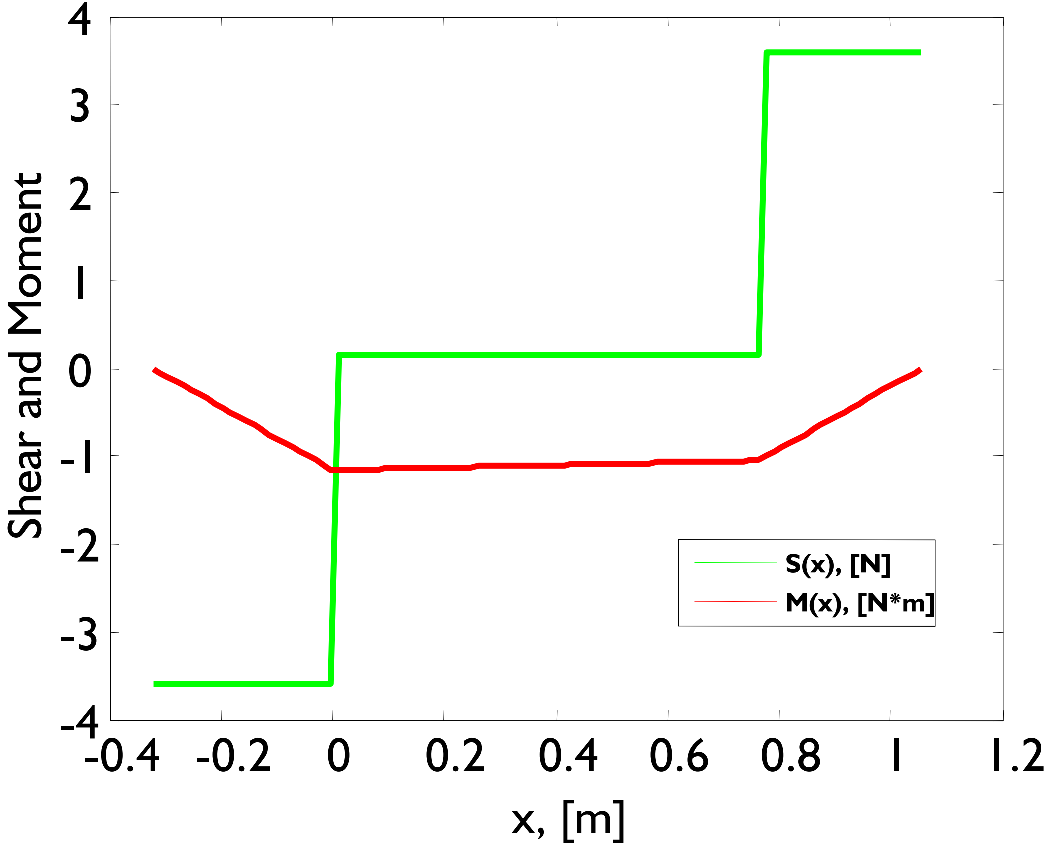
Analytical Model: Simple Beam Theory

- $\sum F = 0$
- $\sum M = 0$

- This is true for any part of the beam:

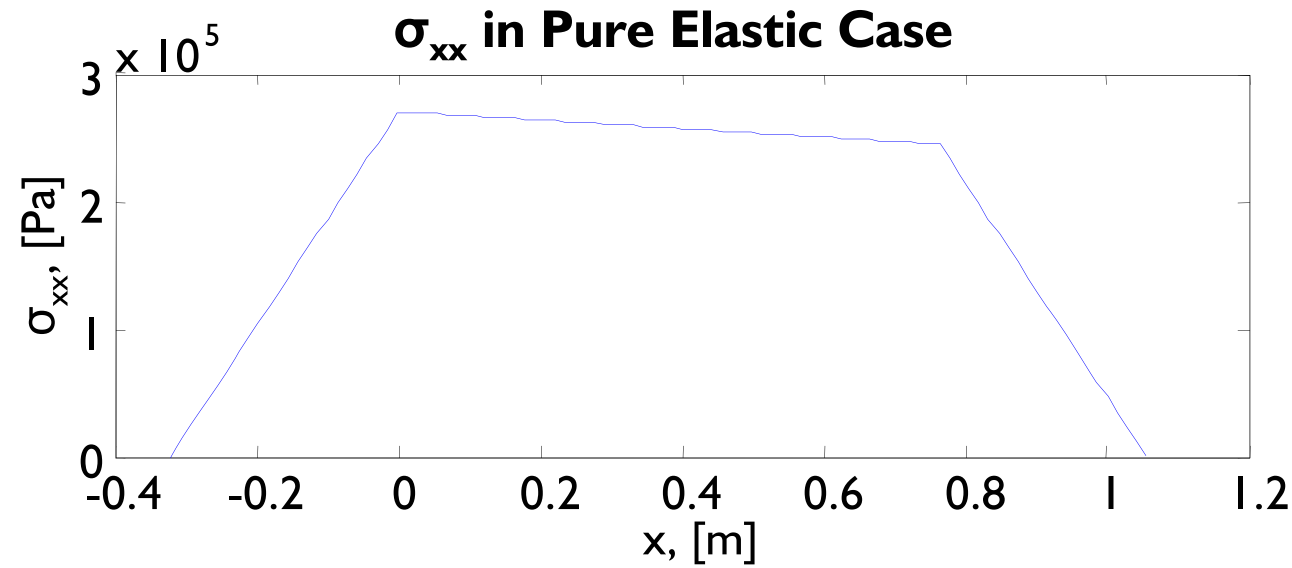


Quartz Tube at Ambient Temperature

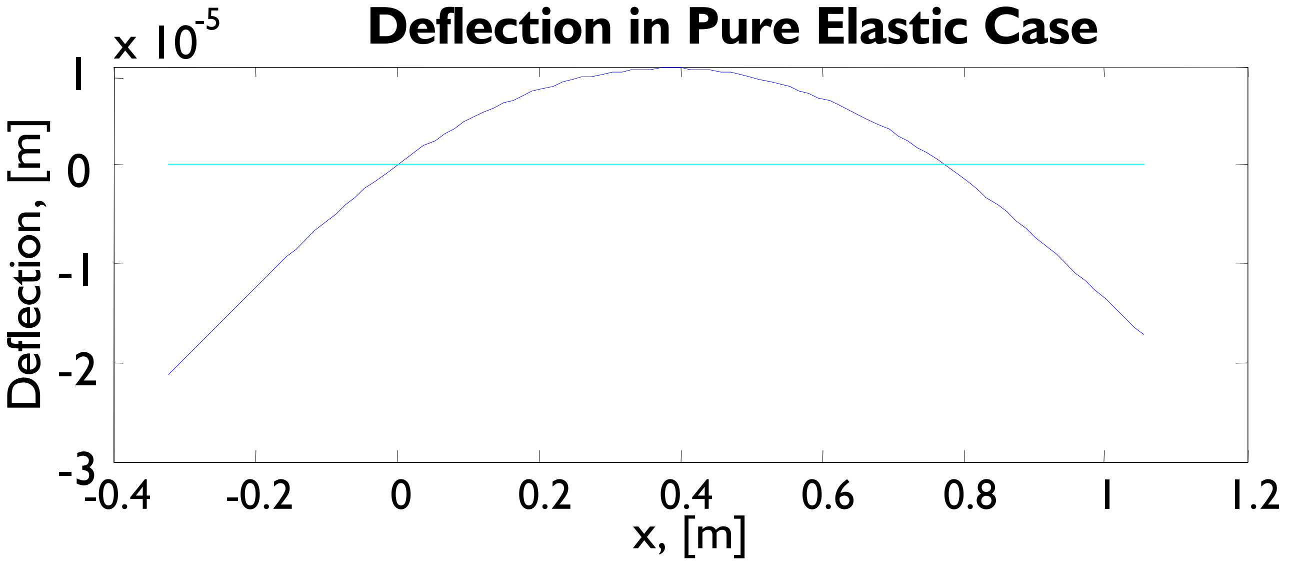


Analytical Model: Simple Beam Theory

$$\sigma_{xx} = -\frac{Mz}{I}$$



$$M = EI\frac{d^2w}{dx^2}$$



Possible Deformation Pathways

Viscoelastic: Deformation is completely reversible ✗

Viscous: Strain rate directly proportional to stress, regardless of stress magnitude; a subcategory of creep ✓

Viscoplastic: Plastic behavior comes into play after the yield stress is reached ✗

Viscosity Equation:

$$\log\eta = \text{-}A + \left[\frac{B}{T - T_0}\right]$$

For Fused Quartz:

Strain Point ($\eta = 10^{13.5}$): 1120°C

Annealing Point ($\eta = 10^{12}$): 1215°C

Glasses behave like “frozen liquids”

Viscous Behavior

Definition of Viscosity From Class:

$$\sigma_{ij} = \eta \underbrace{\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right)}_{=2\text{*strain rate}} + \frac{1}{3}\sigma_{kk}\delta_{ij}$$

This means:

$$\sigma = 3\eta \frac{d\varepsilon}{dt}$$

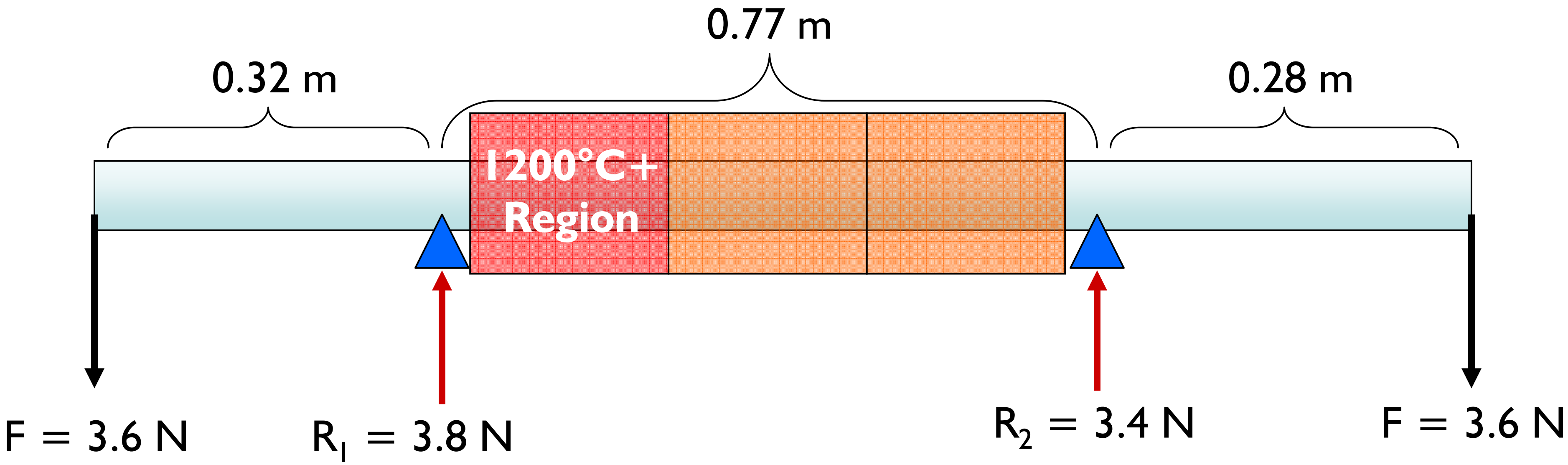
For uniaxial stress

$$\sigma = \eta \frac{d\varepsilon}{dt}$$

For pure shear stress

In beam bending, deflection results from the large σ_{xx}, so we consider a uniaxial stress case

Modifying Simple Beam Theory to Include Viscosity in Hot Zone



- $t = 0$, $\varepsilon = \varepsilon_{elastic}$
- $t > 0$, Furnace runs away,
  - ‘Cool’ regions remain elastic, $\varepsilon = \varepsilon_{elastic}$
  - Hot region starts to viscously flow, $\varepsilon = \varepsilon_{elastic} + \varepsilon_{plastic}$

Viscous Strain

$$\sigma = 3\eta \frac{d\varepsilon}{dt} \longrightarrow \varepsilon_{xx}^{i+1} = \sigma_{xx} / \eta * \Delta t + \varepsilon_{xx}^{i}$$

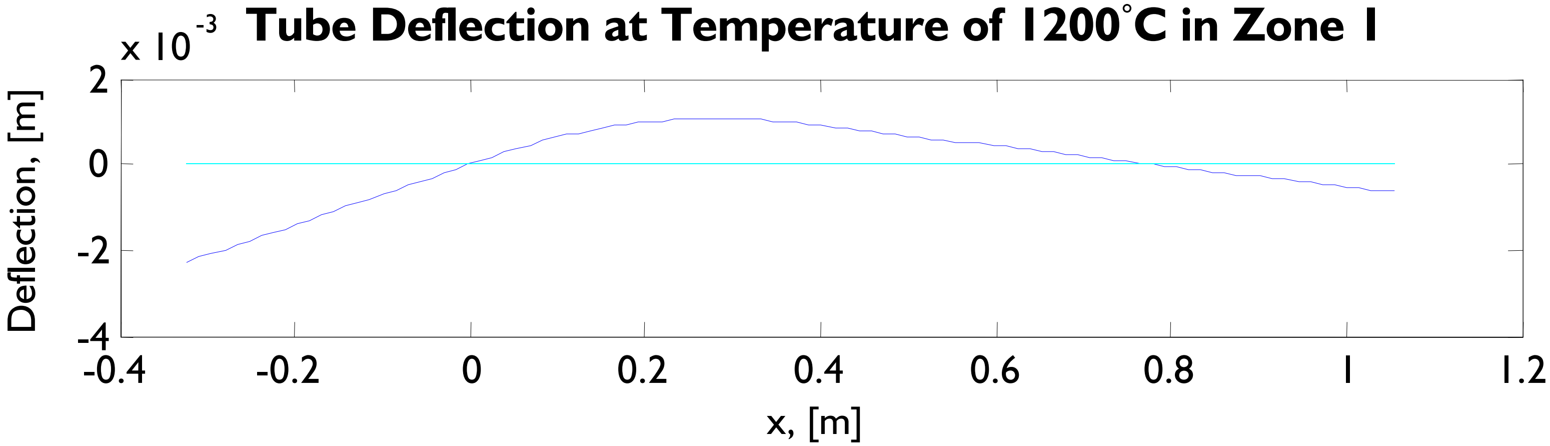
Numerical integration

Where,

- $\sigma_{xx} = f(t)$, from simple beam theory
- $\eta = f(T(t))$, from a given temperature profile, and the derived viscosity equation
- Discretized ε_{xx}^{final} can be fitted with a second order polynomial

We now have all the tools to take a given temperature profile and estimate the tube deflection

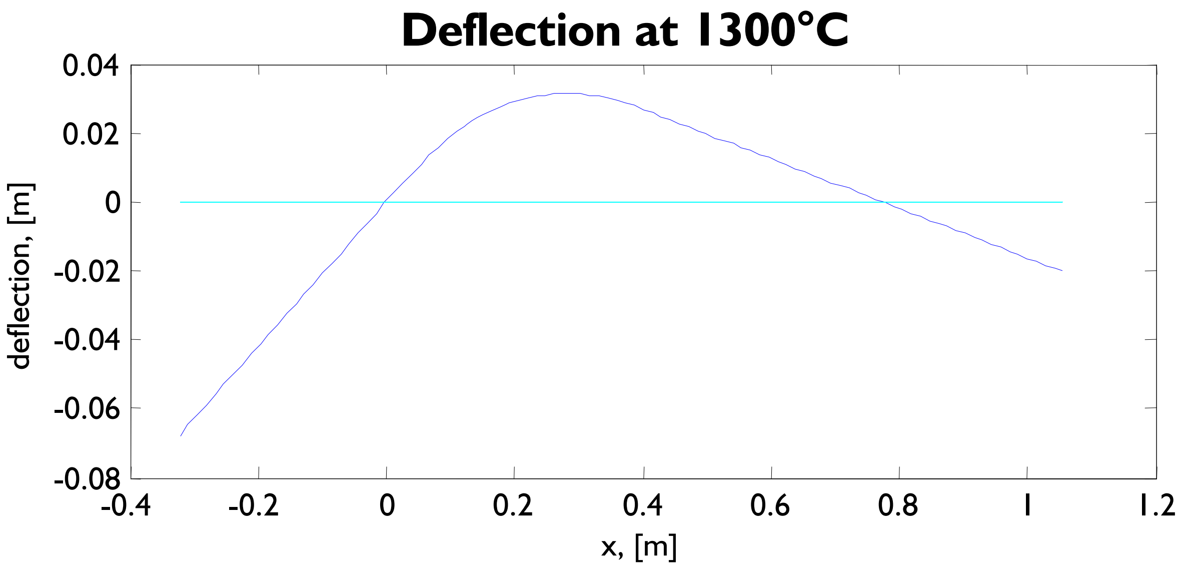
Deflection Results from Model



Contributing Uncertainties:

- 1200°C is the rated maximum temperature max - the maximum temperature 100% duty cycle is likely higher
- Model only allows concave down curvature while tube exhibits some concave up behavior in Zone 2
- Temperature surrounding Zone 1 (in ceramic collar and in Zone 2) is uncertain

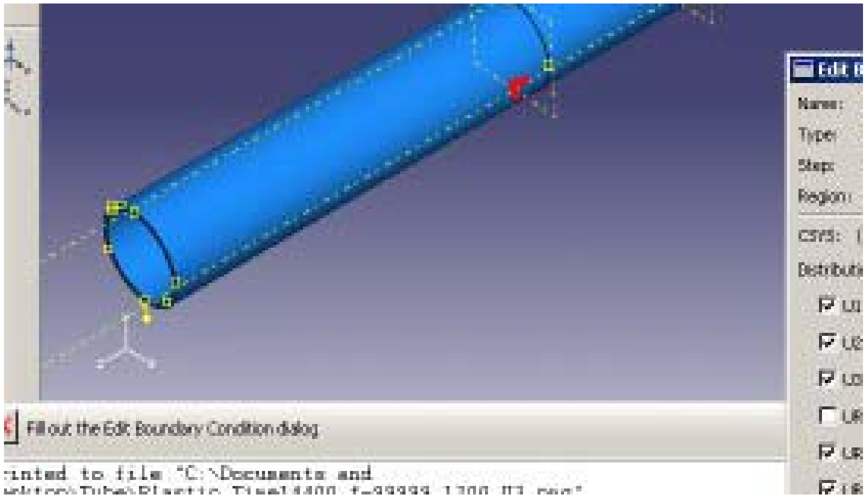
Deflection Results from Model: Higher Temperatures



Zone 1 Temperature	Max Deflection, Left	Max Deflection, Top
1200°C	-0.22 cm	0.11 cm
1250	-1.4 cm	0.60 cm
1275	-3.0 cm	1.4 cm
1300	-6.9 cm	3.3 cm
Actual	-9.7 cm	3.4 cm

Finite Element Model

- Run in ABAQUS 6.7.1
- Objectives were to get a functional model and to observe phenomena not captured by simple beam theory
- Used two approaches:
  - Standard 3D deformable solid with a higher compliance in Zone 1 (to identify behaviors due to large deflections)
  - Full coupled temperature-displacement model (to simulate viscous flow)



Fill out the Edit Boundary Condition dialog

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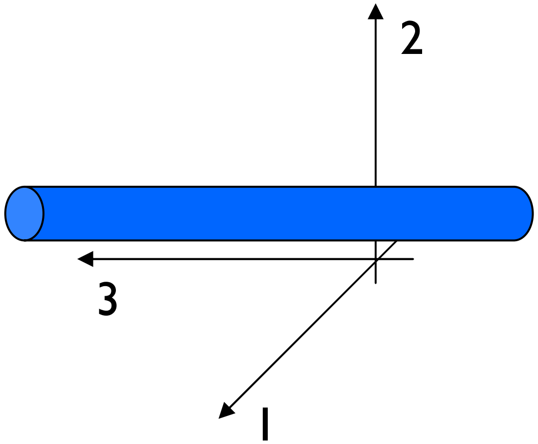
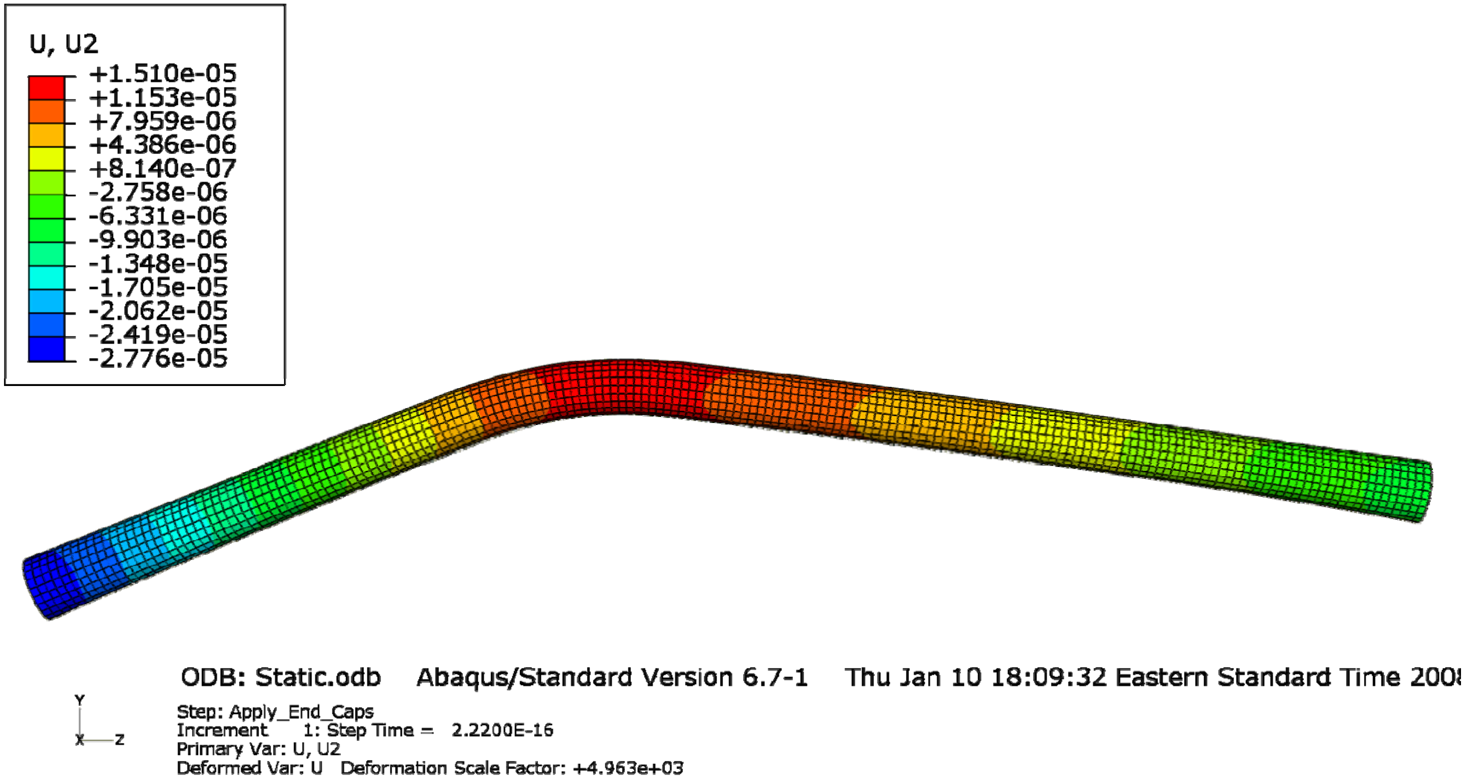


3D Deformable Solid



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ODB: Static.odb    Abaqus/Standard Version 6.7-1    Thu Jan 10 18:09:32 Eastern Standard Time 200
Step: Apply_End_Caps
Increment     1: Step Time =    2.2200E-16
Primary Var: U, U2
Deformed Var: U   Deformation Scale Factor: +4.963e+03
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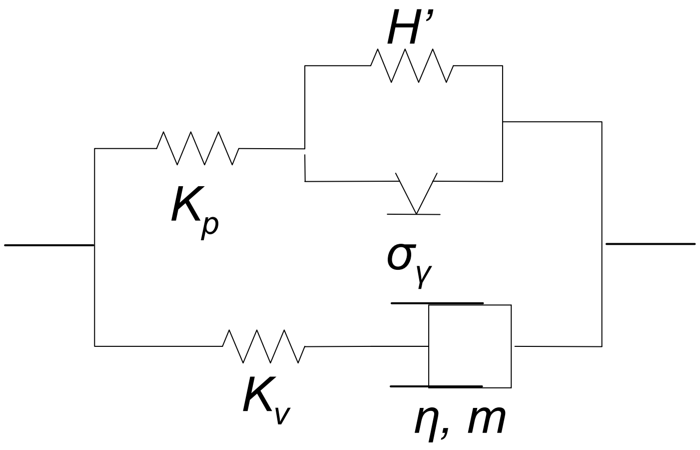
- Defined Zone 1 region with a Young's modulus of 2 GPa, rest of tube with 70 GPa
- Observed similar shape trend as beam theory, but deflections were four orders of magnitude off
- Suggests concave section in Zone 2 results from plasticity

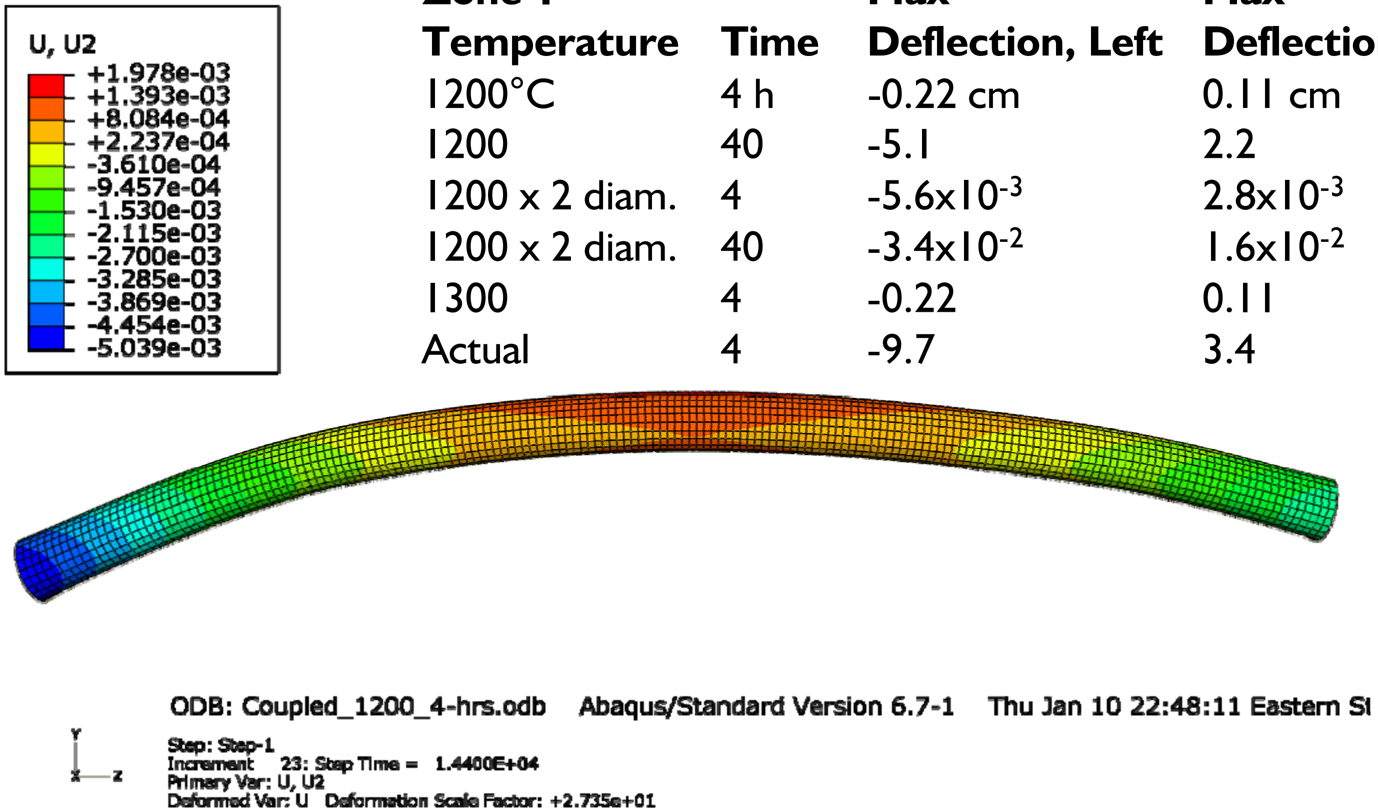
Coupled Temperature-Displacement

- ABAQUS models viscous flow using a two-layer viscoplasticity model - requires defining elastic, plastic, and viscous components (viscous $A=5.7836\text{x}10^{-13}$, $n=1$, $m=0$, $f=0.99999$)
- Must define thermal conductivity and specific heat
- Used a C3D8T element type
- Divided tube into seven regions, assigned temperatures as "Initial Conditions"
- Boundary conditions: U1, U2, U3, UR2, and UR3 restricted where tube contacted edge of ceramic collars
- Modeled Zone 1 at 1200°C-1300°C for 4-40 hrs.



Coupled Temperature-Displacement 1200°C, 4 hrs.

Zone 1 Temperature	Time	Max Deflection, Left	Max Deflection, Top
1200°C	4 h	-0.22 cm	0.11 cm
1200	40	-5.1	2.2
1200 x 2 diam.	4	$-5.6x10^{-3}$	$2.8x10^{-3}$
1200 x 2 diam.	40	$-3.4x10^{-2}$	$1.6x10^{-2}$
1300	4	-0.22	0.11
Actual	4	-9.7	3.4



- Shape trend was different from simple beam theory/actual data
- Similar deflections only observed after 40 hrs., significantly longer than actual experiment time

Conclusions

- General bending behavior captured with simple beam theory and finite element models
- The deformations resulting from the viscous behavior in the fused quartz are significantly impacted by temperature, time
- Concave dip in Zone 2 region implies some information is missing regarding the temperature profile in this zone
- Temperature was likely hotter than 1200°C
- Pinching at the top of the tube is not a direct result from tube bending or from viscous flow - likely because of impeded deflection against thermocouple
- Accurate viscous deformations are difficult to model in ABAQUS