

Estimation of Delamination Contact Resistance in Composites

William P. Winfree*, Joseph N. Zalameda and Patricia A. Howell

NASA Langley Research Center Hampton, VA 23681

2021 Thermosense Virtual Conference: April 11-15, 2021

*NASA Retired

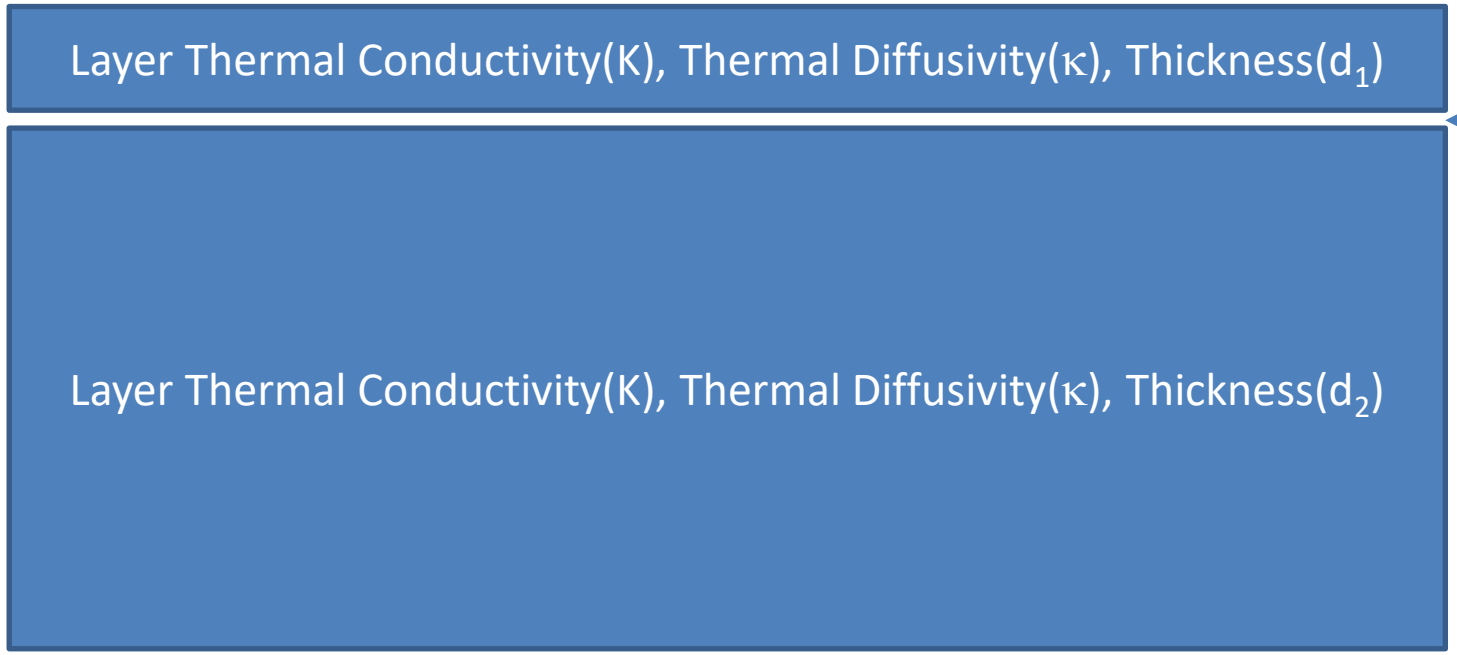
Overview

- Simulations assist in developing an understanding of the limitations of the technique and enable quantitative characterization of subsurface flaws
- Quadrupole Method is a method for rapid simulation of thermographic inspection of composites
- Examine the sensitivity of simulation to in-plane diffusivity and delamination gap spacing
- Based on the computed tomography characterization of impact damage in a composite, simulate the thermal response
- Compare the simulation results to experimental measurements
- Iterate on gap width to improve agreement between simulation and experiment

Quadrupole Method

- Solves Laplace transform of heat equation, then inverts to temporal solution
- Used extensively for 1-D layered systems
- Extended to 3-D in particular for composite
  - Previous methodology developed for single delamination at an interface between two layers
    - Batsale, J., Maillet, D., and Degiovanni, A., International Journal of Heat and Mass Transfer 37 (1), 111, (1994).
    - Bendada, A., Modelling and Simulation in Materials Science and. Engineering 10 (6), 673 (2002).
    - Bendada, A., Erchiqui, F., and Lamontagne, M Inverse Problems 21 (3), 85 (2005)
    - Winfree,W., Zalameda, J., Howell,P., and Cramer, E., Proc. SPIE 9861, Thermosense: Thermal Infrared Applications XXXVIII, 98610N (11 May 2016);
  - Methodology developed for multiple delaminations at multiple interfaces between layers and plates that are not aligned
    - Winfree, W., Zalameda, J. and Howell, P., Proc. SPIE 11004, Thermosense: Thermal Infrared Applications XLI, 110040F (2 May 2019)
    - Winfree, W., Zalameda, J. and Howell, P., Thermosense: Thermal Infrared Applications XLII; 114090K (2020)

One-Dimensional Model of Two Layer System with Air Gap



Thin Air Gap
d_{gap} Thickness
K_{air} Thermal Conductivity of Air

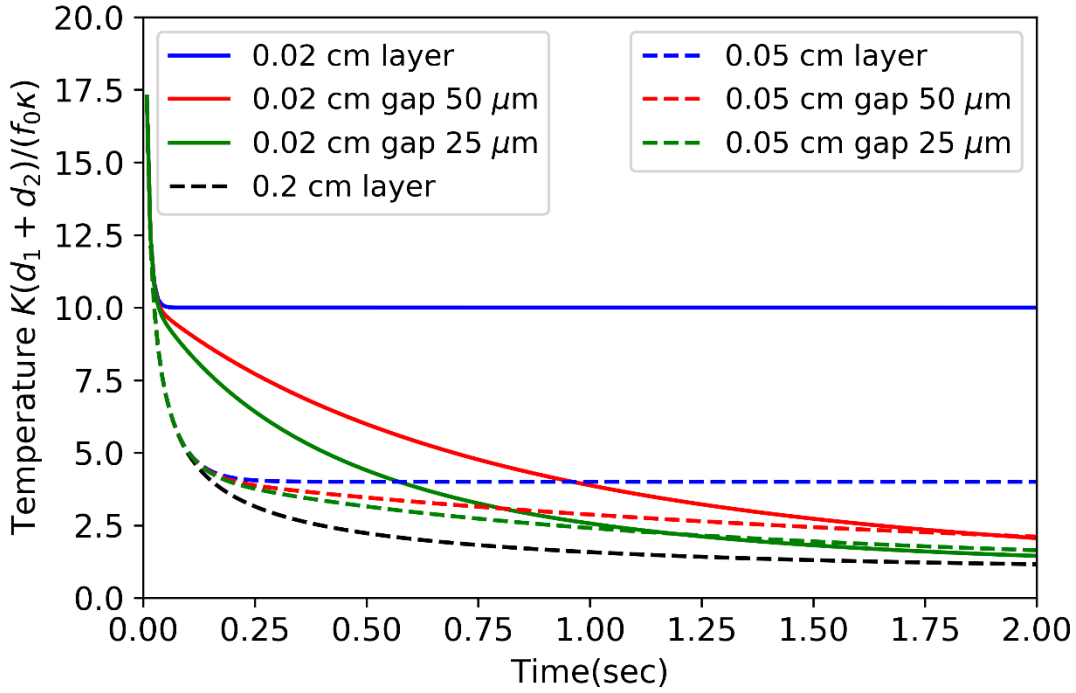
For thin air gap, the thermal properties of the air gap can be represented by a contact resistance R which is equal to thickness of the air gap divided by the thermal conductivity of the air gap.

In equations R is always multiplied by thermal conductivity of layer, such that relevant term is $K\, d_{gap}/K_{air}$

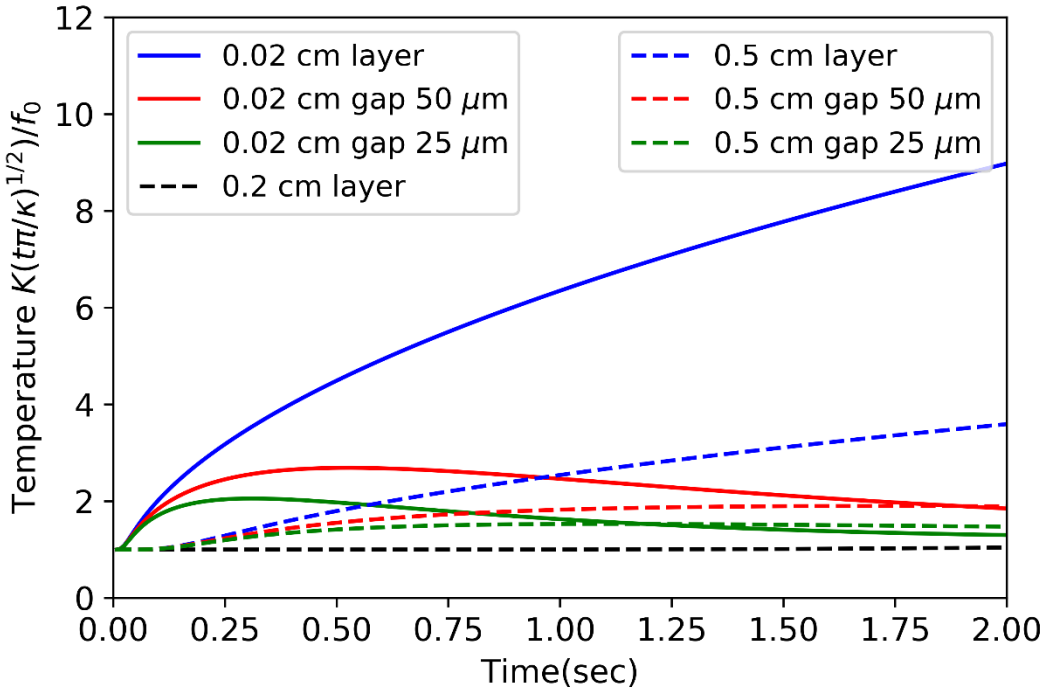
Gap Width Influence on One-Dimensional Thermal Response

First layers are 0.02 cm and 0.05 cm thick
Second layers are 0.18 and 0.15 cm thick

Two different representation of the same data



Normalized by dividing by the combined heat capacities of the two layer and the input flux. For long times approaches 1 if contact resistance is less than infinity



Normalized by dividing by the response of a semi-infinite layer with the same thermal properties and the input flux. Thermal response is 1 for early times.

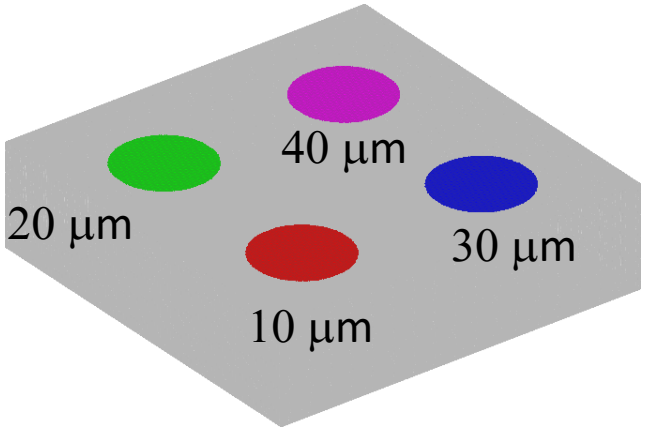
Gap Width Influence on Three-Dimensional Thermal Response

First layer is 0.02 cm and thick Second layer is 0.18 cm thick

Normalized by dividing by the response of a semi-infinite layer with the same thermal properties and the input flux.

In-plane and surface normal diffusivities are both 0.005 cm^2/sec

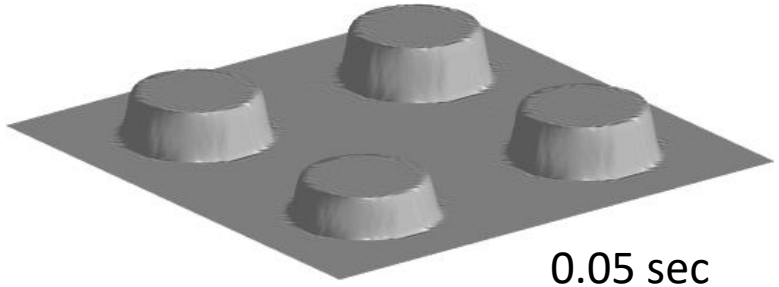
Air Gaps Widths



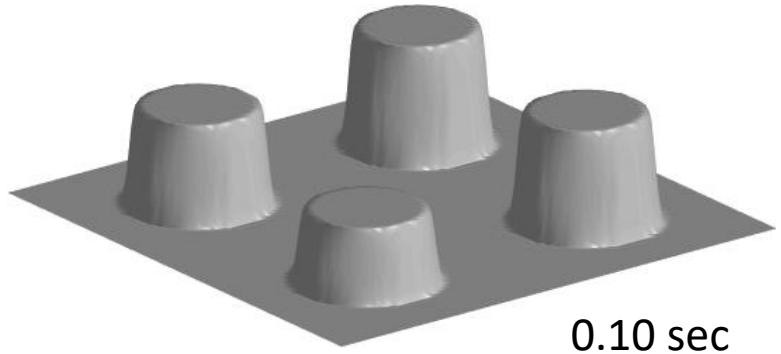
Diameter of circular air gaps 1 cm

Block 4 x 4 x 0.2 cm

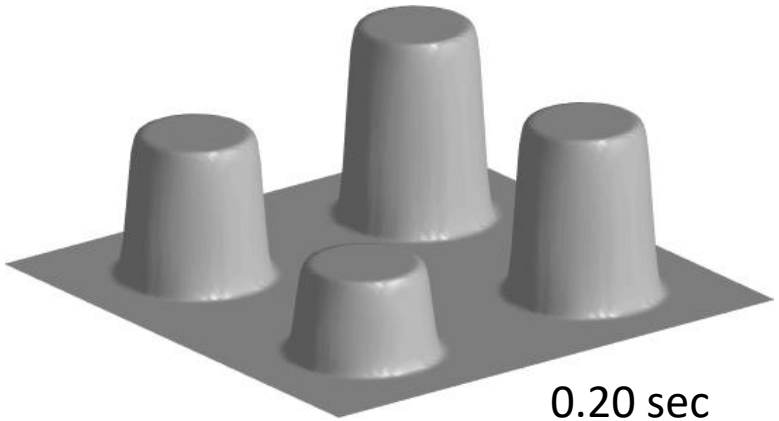
Aspect ratio (1,1,5)



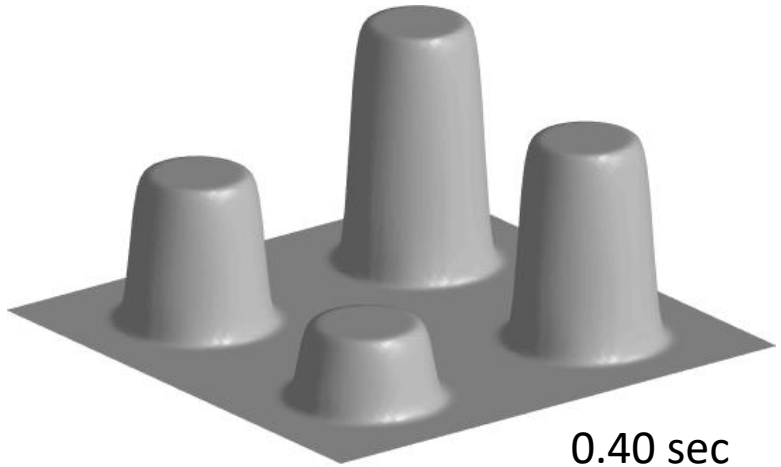
0.05 sec



0.10 sec



0.20 sec



0.40 sec

Same scaling for all surface plots

NASA Langley Research Directorate

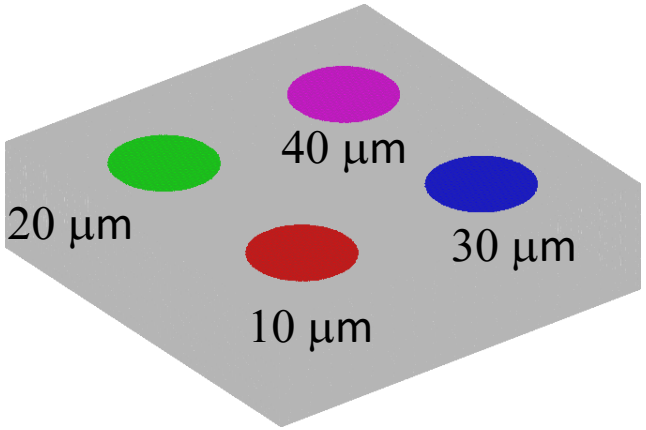
Gap Width Influence on Three-Dimensional Thermal Response

First layer is 0.02 cm and thick Second layer is 0.18 cm thick

Normalized by dividing by the response of a semi-infinite layer with the same thermal properties and the input flux.

In-plane diffusivity is 0.025 cm^2/sec and surface normal diffusivity is 0.005 cm^2/sec

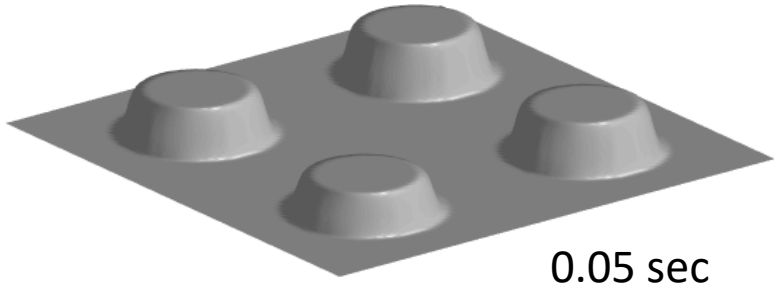
Air Gaps Widths



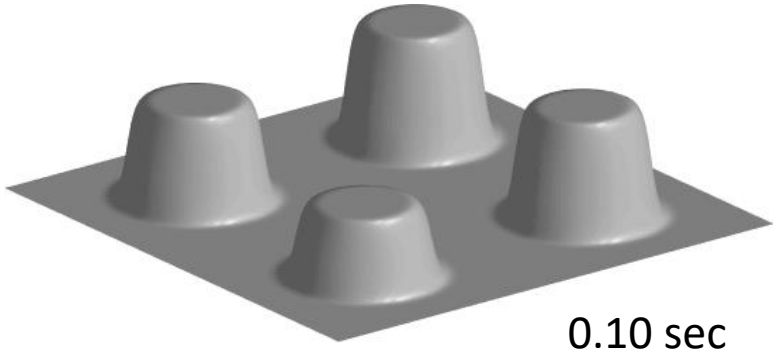
Diameter of circular air gaps 1 cm

Block 4 x 4 x 0.2 cm

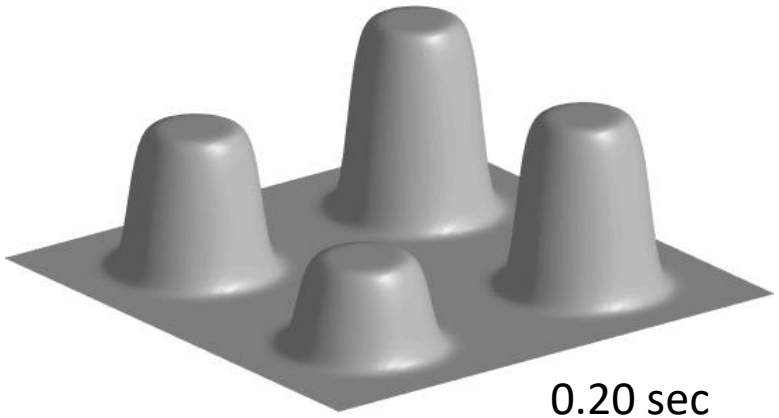
Aspect ratio (1,1,5)



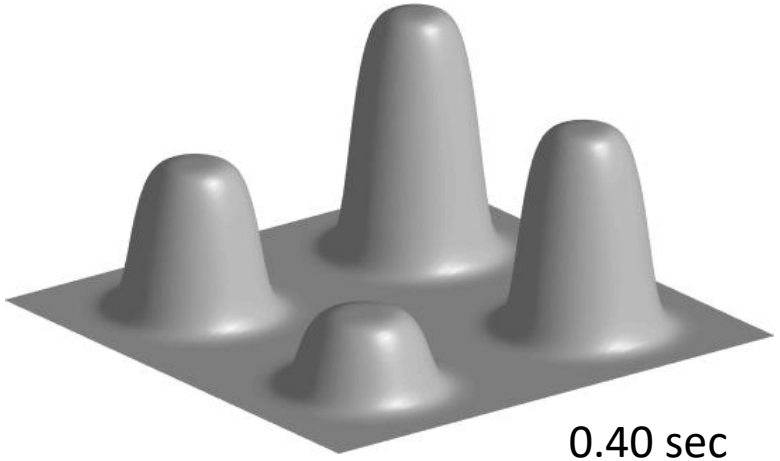
0.05 sec



0.10 sec



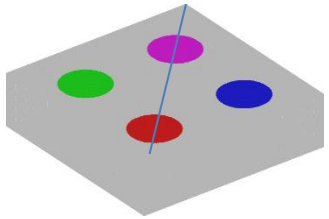
0.20 sec

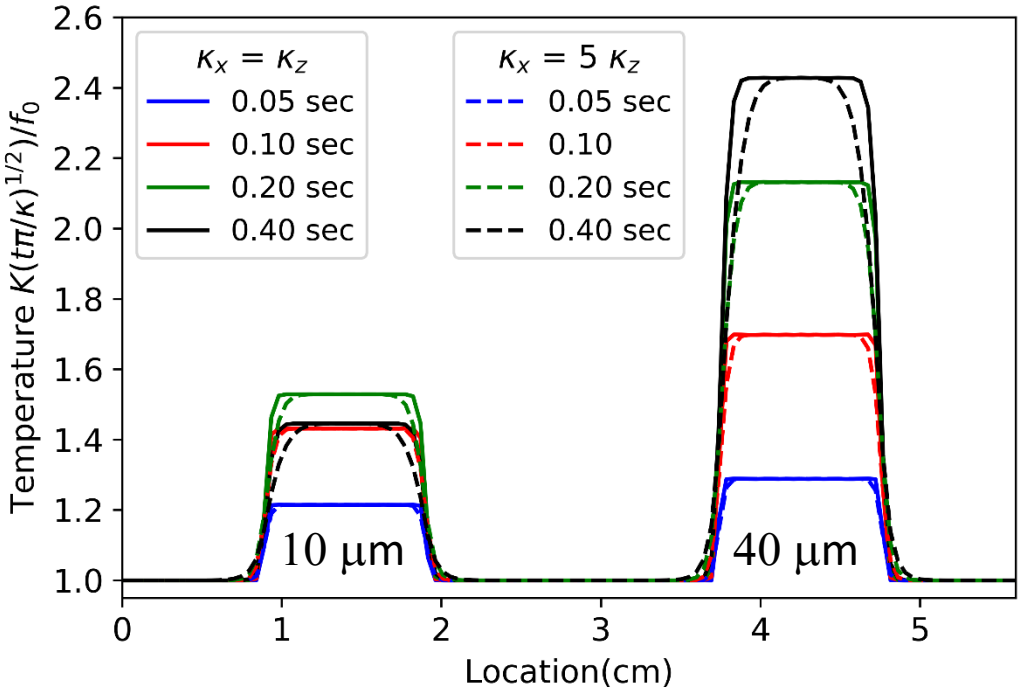


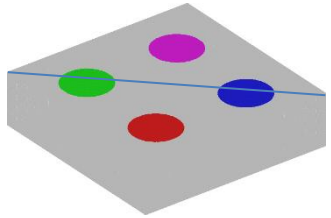
0.40 sec

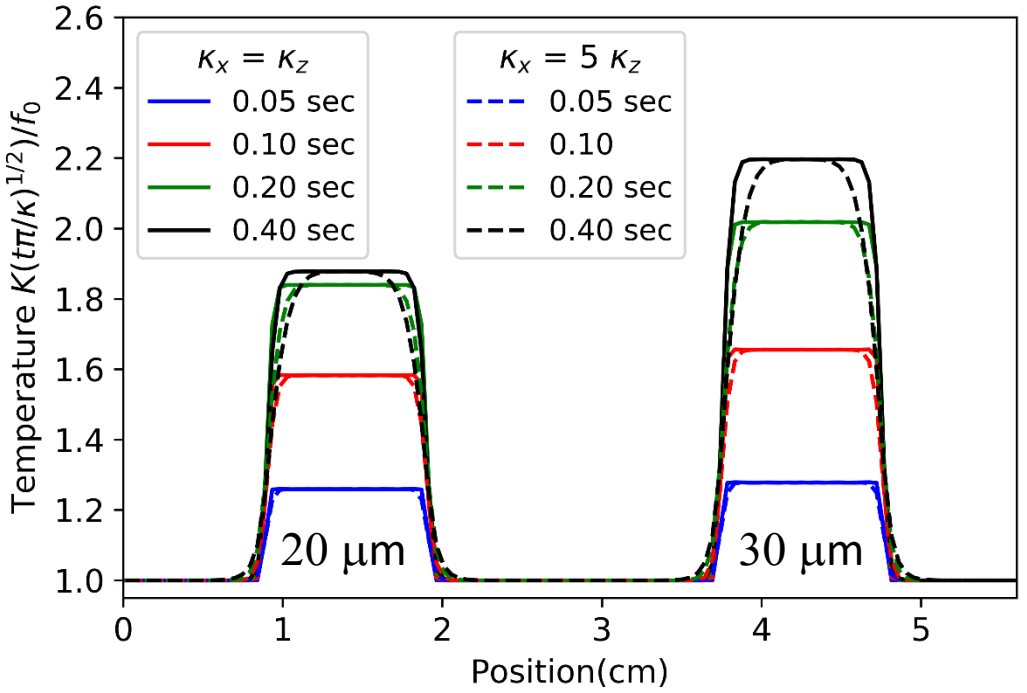
Same scaling for all surface plots

Temperature Profiles Along Diagonals of Three-Dimensional Thermal Responses







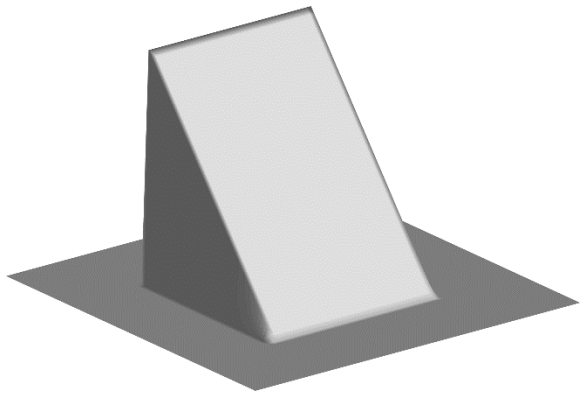


Over the 10 μm air gap the thermal contrast decreases between 0.2 sec and 0.4 sec

Over the 20 μm air gap the thermal contrast does not significantly increase between 0.2 sec and 0.4 sec

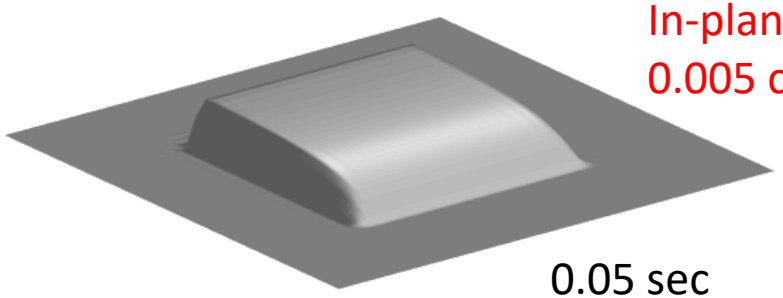
Three-Dimensional Thermal Response for Wedge Gap

First layer is 0.02 cm thick. Second layer is 0.18 cm thick
Surface normal diffusivity is 0.005 cm^2/sec

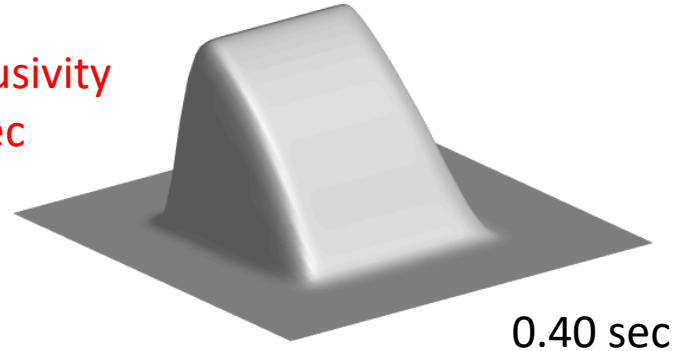


Wedge air gap between first and second layers varies from 0 to 40 μm
Layer 2 cm x 2 cm
Wedge 1 cm x 1 cm

In-plane diffusivity
0.005 cm^2/sec

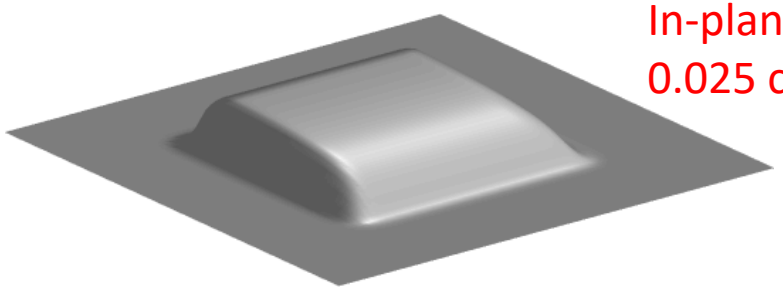


0.05 sec

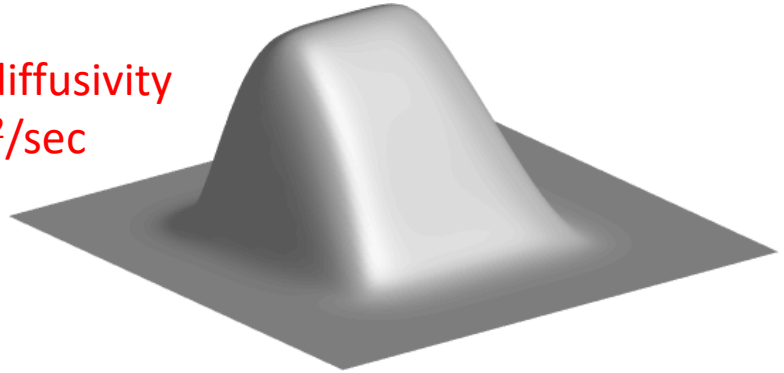


0.40 sec

In-plane diffusivity
0.025 cm^2/sec



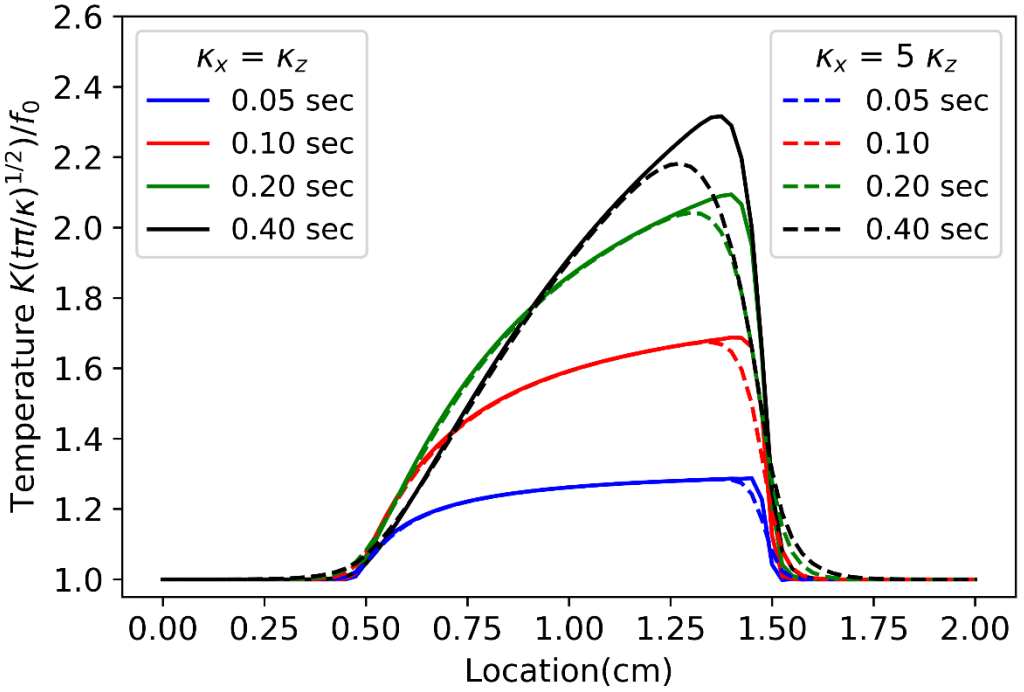
0.05 sec

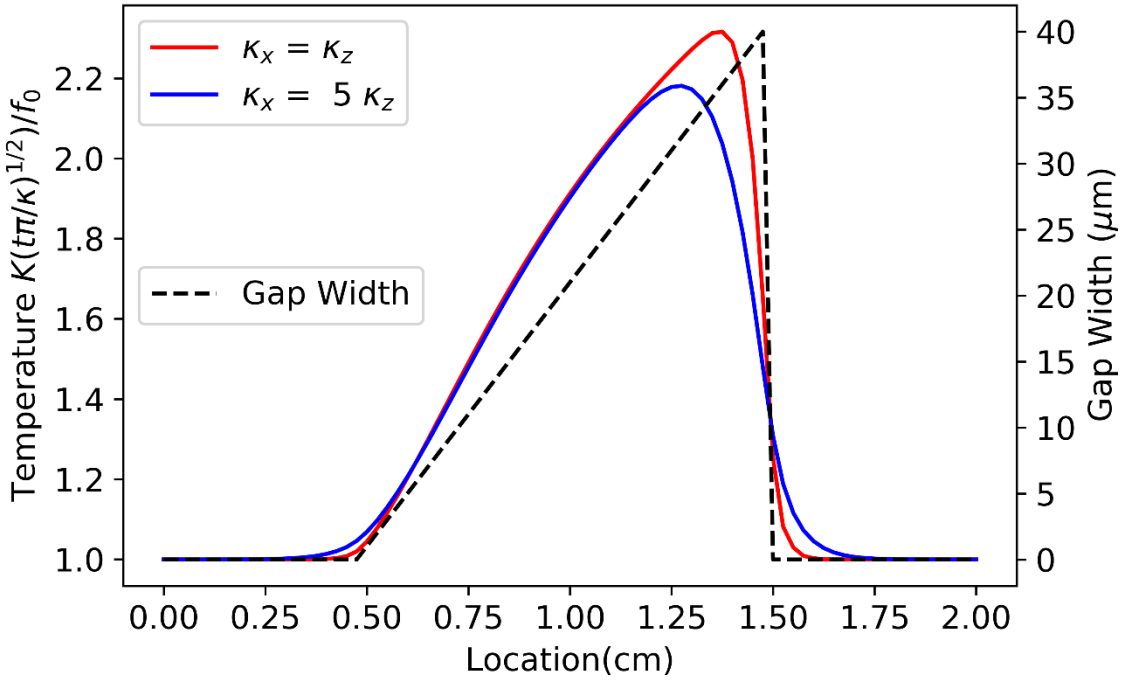


0.40 sec

Same scaling for all surface plots

Temperature Profiles Along Wedge Center



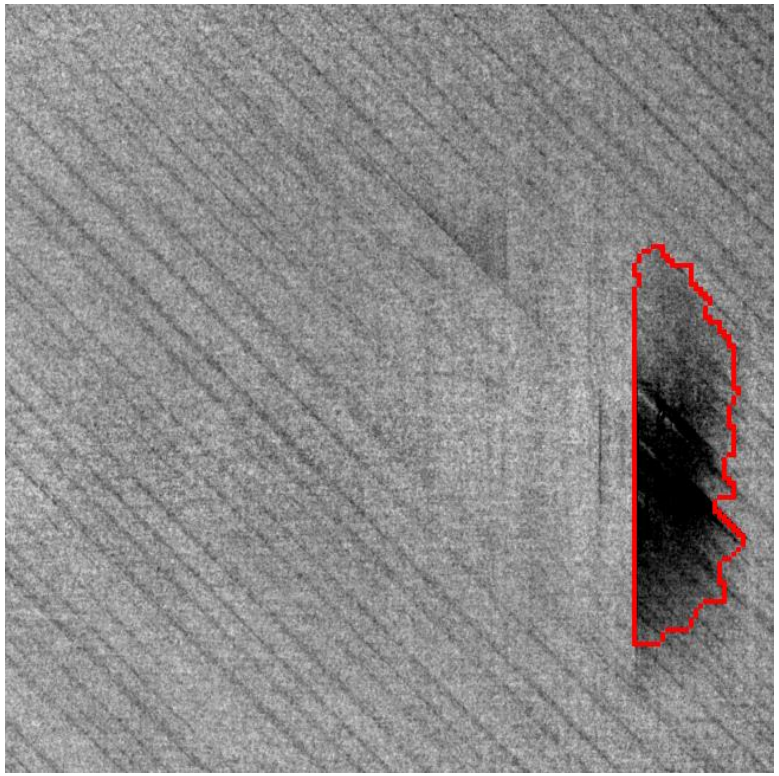


Initial time response does not reflect the shape of the wedge
Later time response does reflect the shape of the wedge
Increasing in-plane diffusivity by a factor of 5 does not dramatically change response

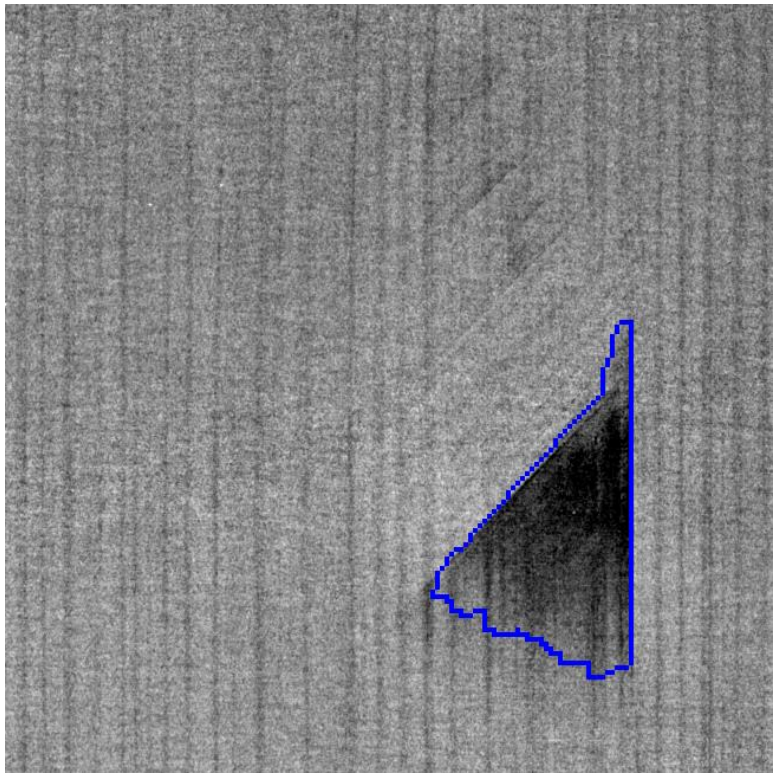
CT Estimation of Impact Damage Composite

NASA Langley Research Directorate

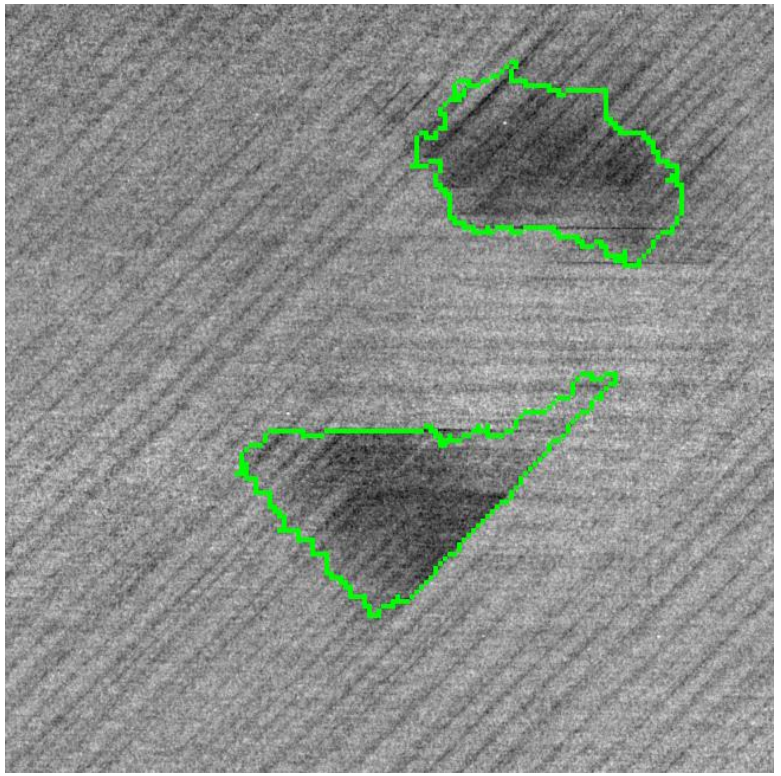
Region 2.6 cm by 2.6 cm



0.018 cm below surface

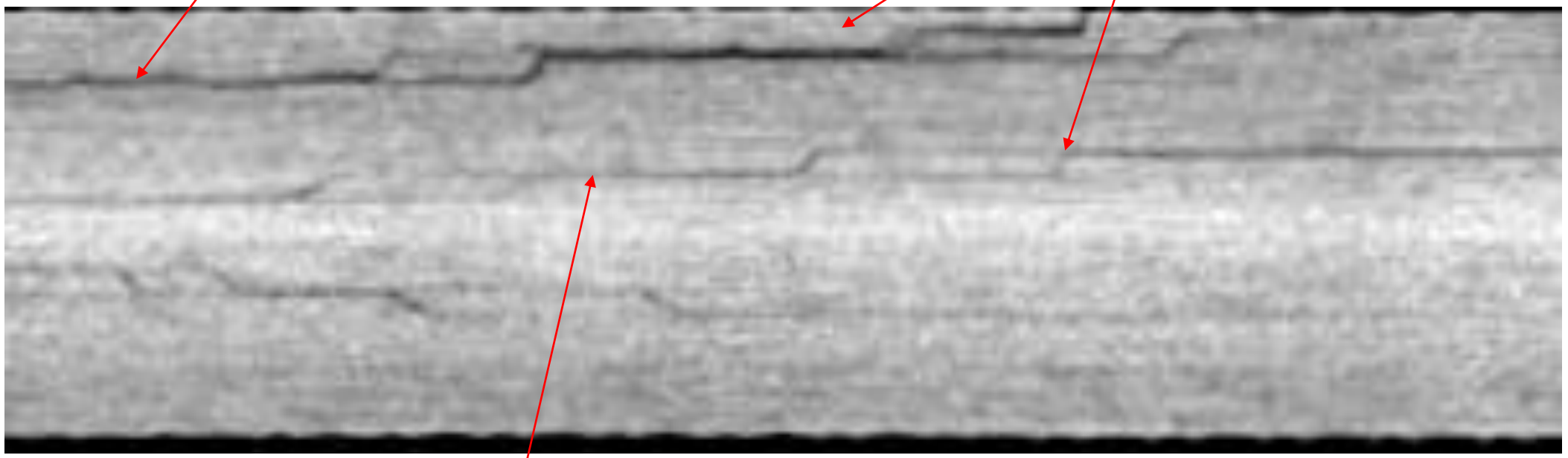


0.036 cm below surface

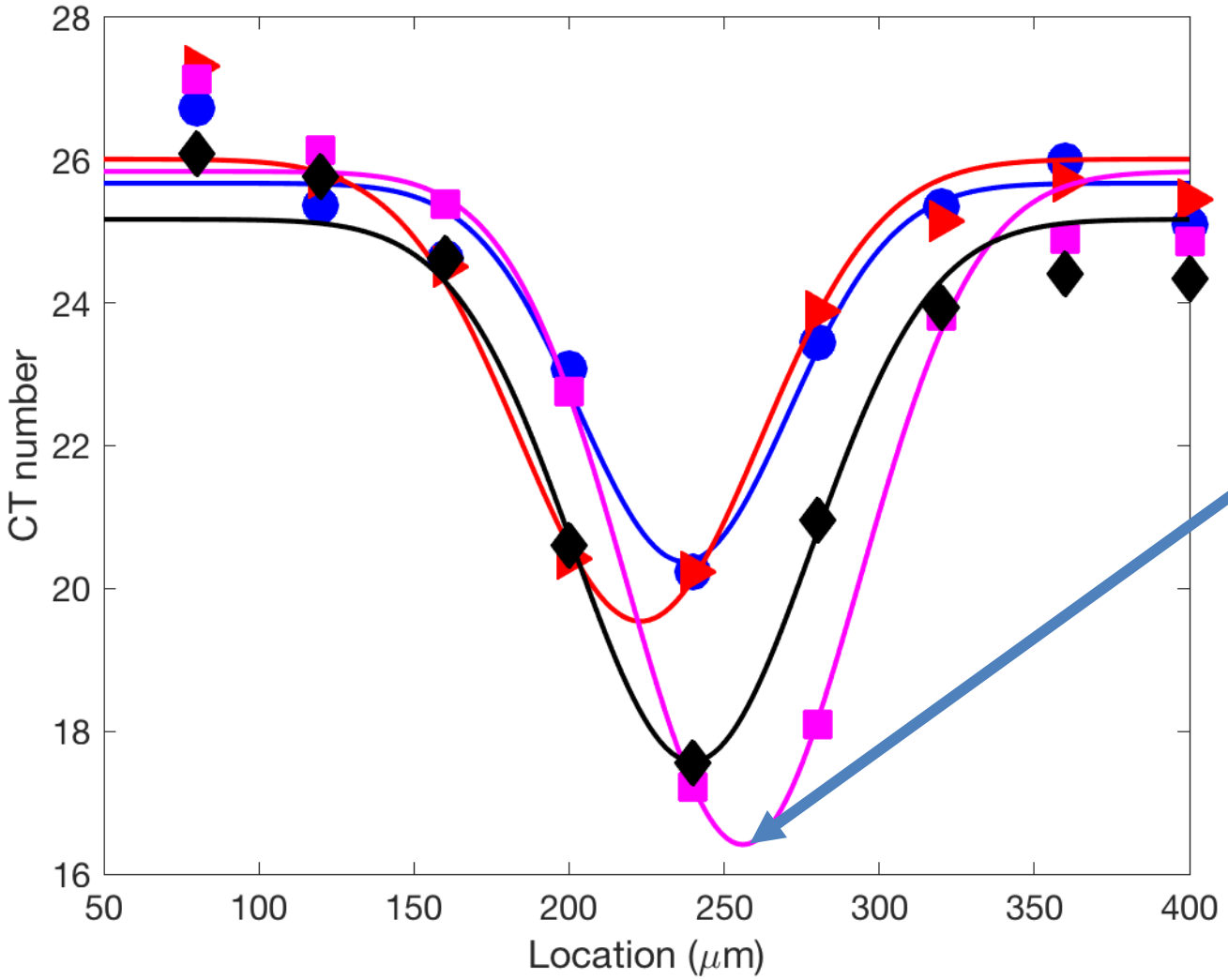


0.054 cm below surface

CT Data Through an Impacted Region of the of the Composite



Gaussian Fit for Calculation of Gap Width



Fit with a constant minus a Gaussian.

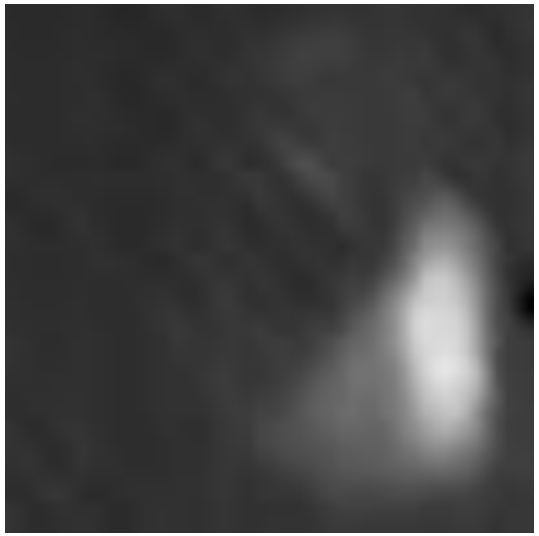
Amplitude of the Gaussian proportional to the gap width

Point spread of CT system estimated from CT response at edge of composite

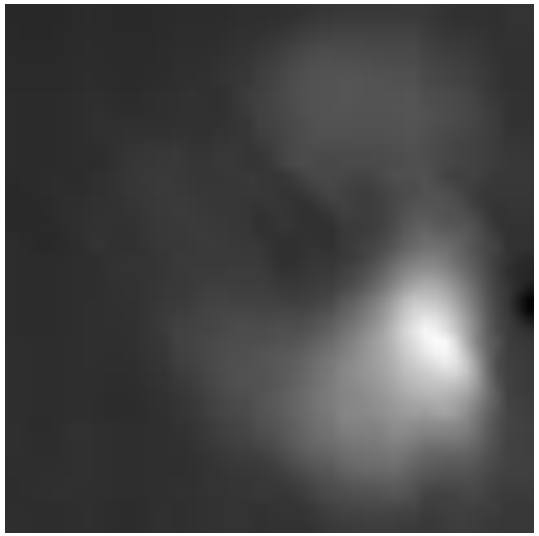
Quadrupole Simulation of Impacted Composite

- Gap spacings map is multiplied by the thermal conductivity of air to provide a contact resistance map at interfaces identified by CT as having a delamination
- Largest gap thickness ~ 50 μm
- Thermal conductivity composite: 97000 Erg/(cm K sec)
- Diffusivity: 0.0044 cm^2/sec
- Thermal conductivity of air: 2624 Erg/(cm K sec)
- Largest $K_{composite}$ R is ~0.18 cm

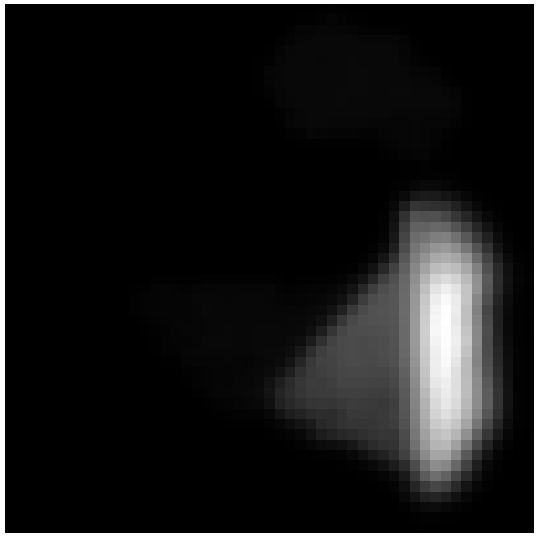
Image Comparison of Simulation to Experimental Data



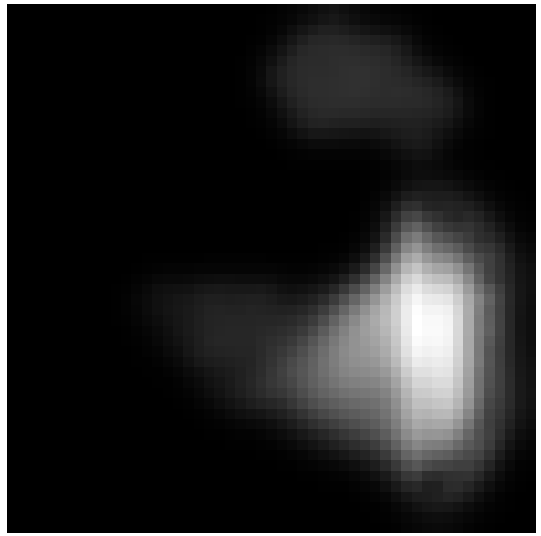
Region 2.6 cm by 2.6 cm



Measured Response



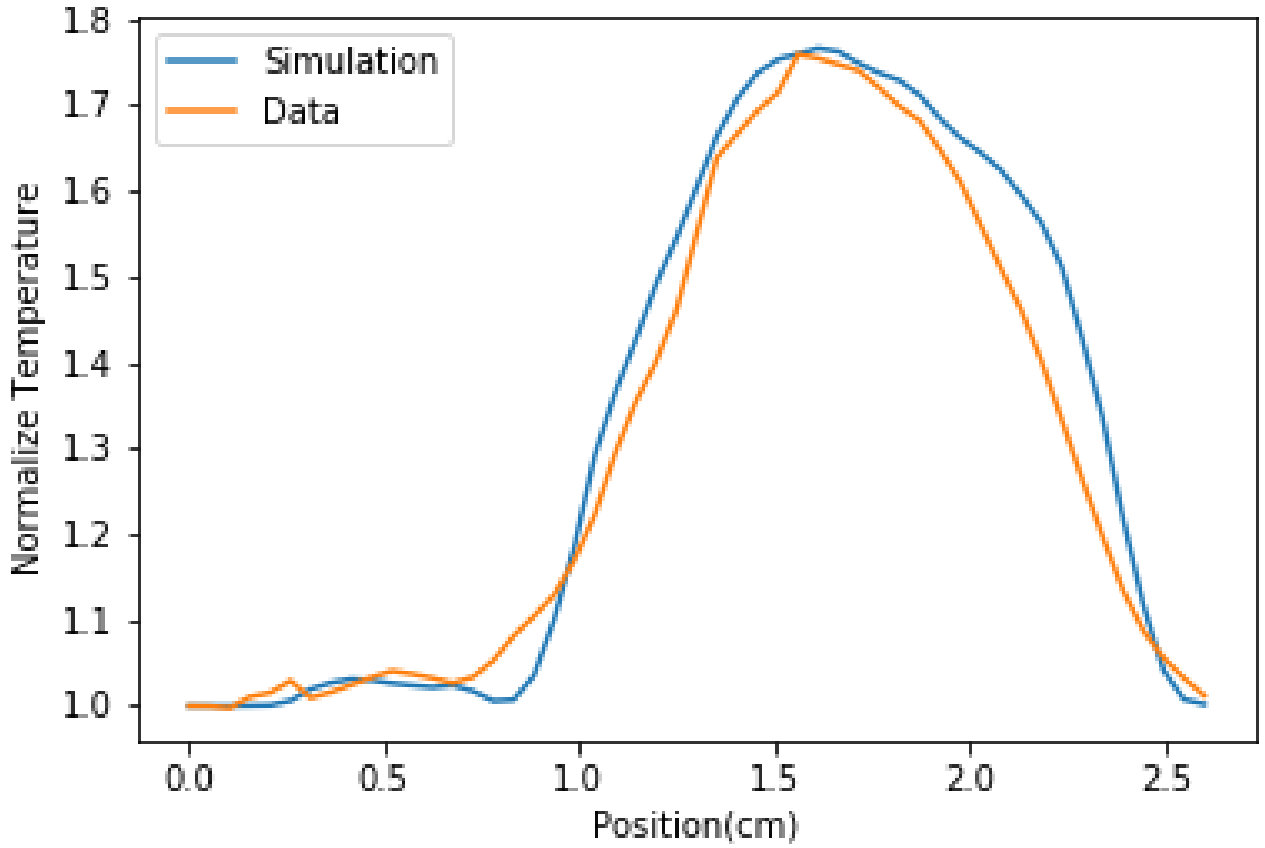
Simulation Response

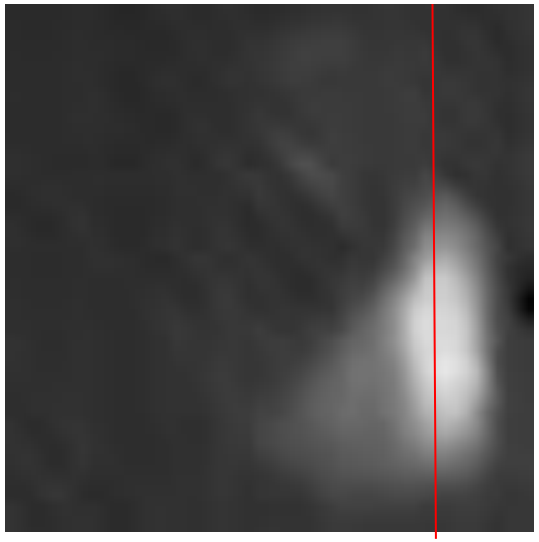


1/6 sec

0.40 sec

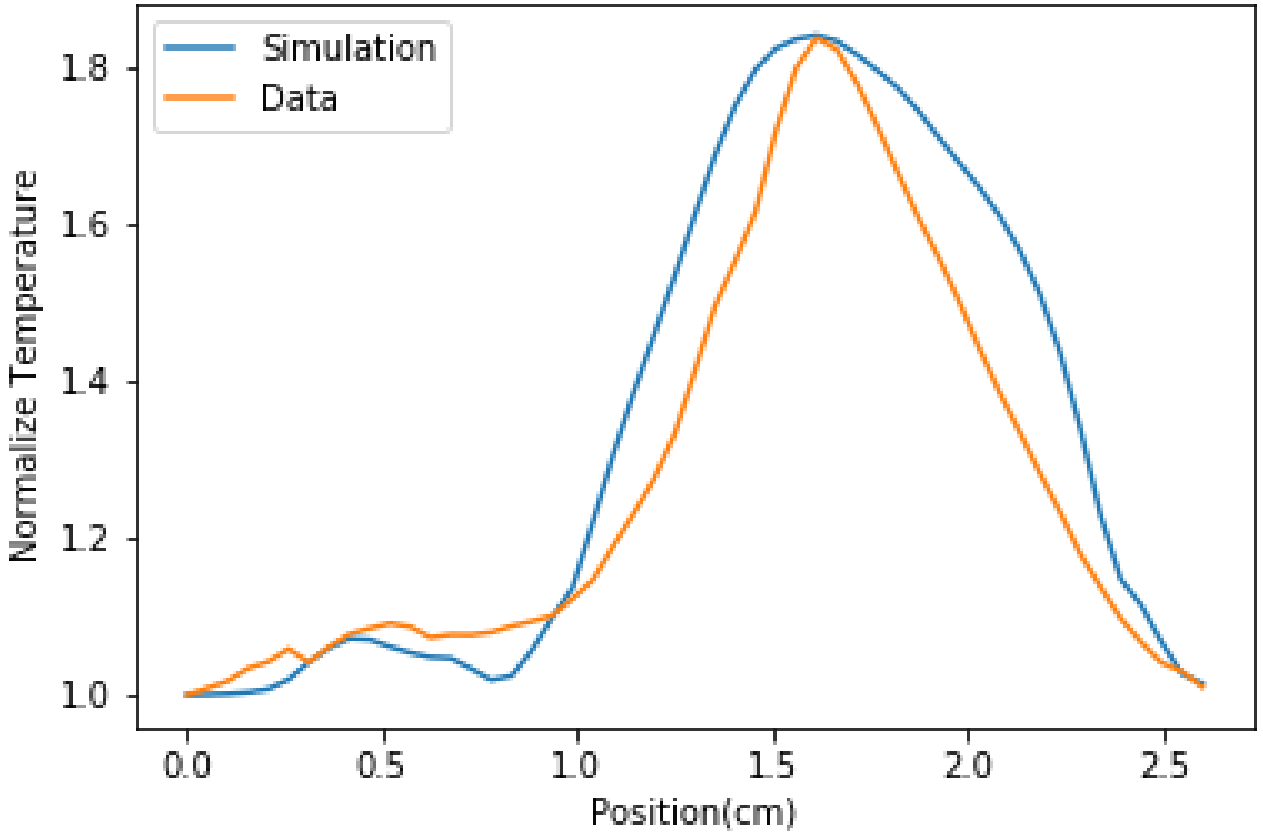
Vertical Profiles of Experimental Data and Simulation Data at 1/6 sec

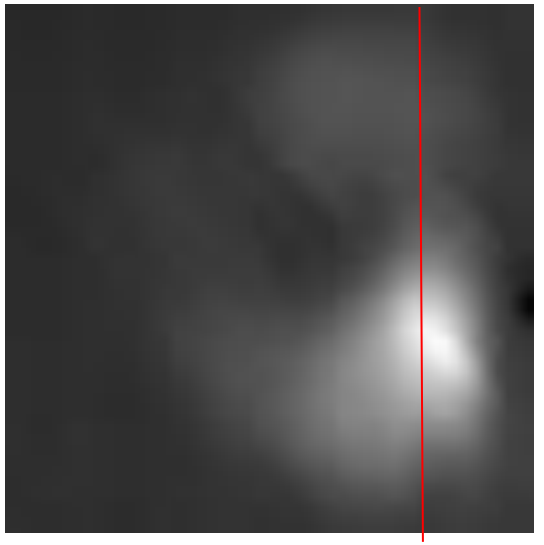




Delamination closest to surface

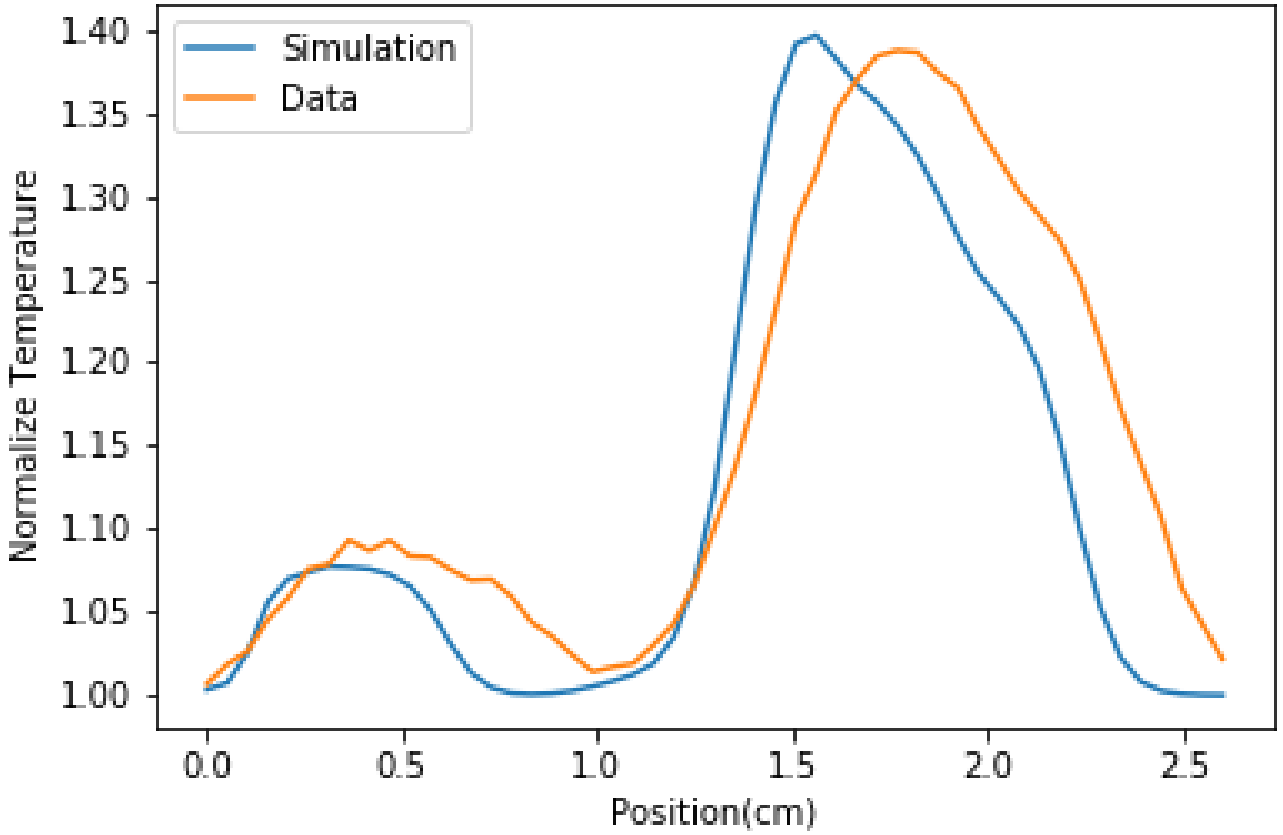
Vertical Profiles of Experimental Data and Simulation Data at 0.4 sec

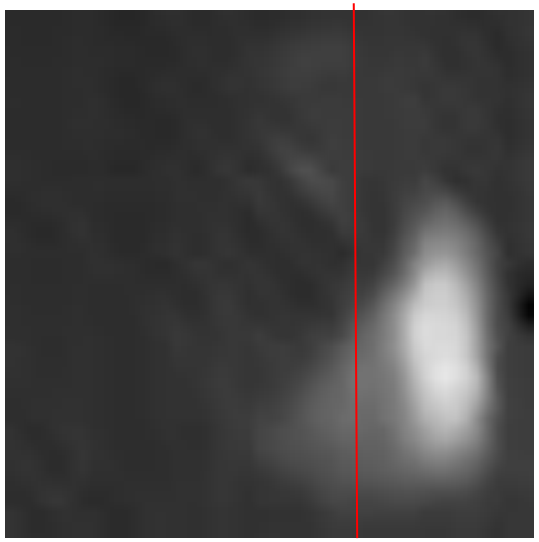




Delamination closest to surface

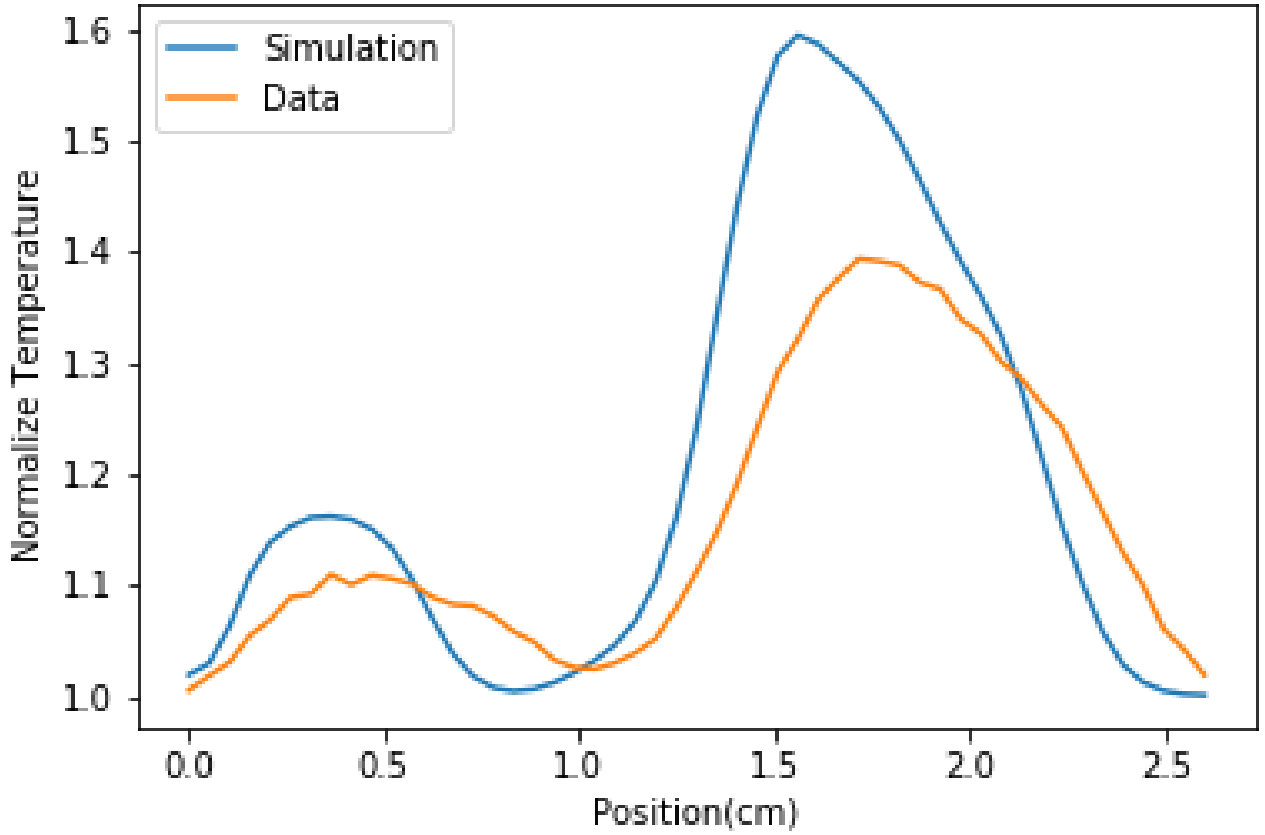
Vertical Profiles of Experimental Data and Simulation Data at 1/6 sec

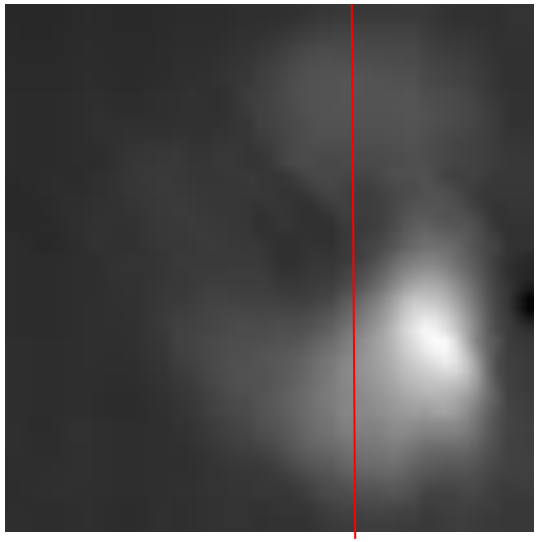




Delamination 0.36 cm from surface

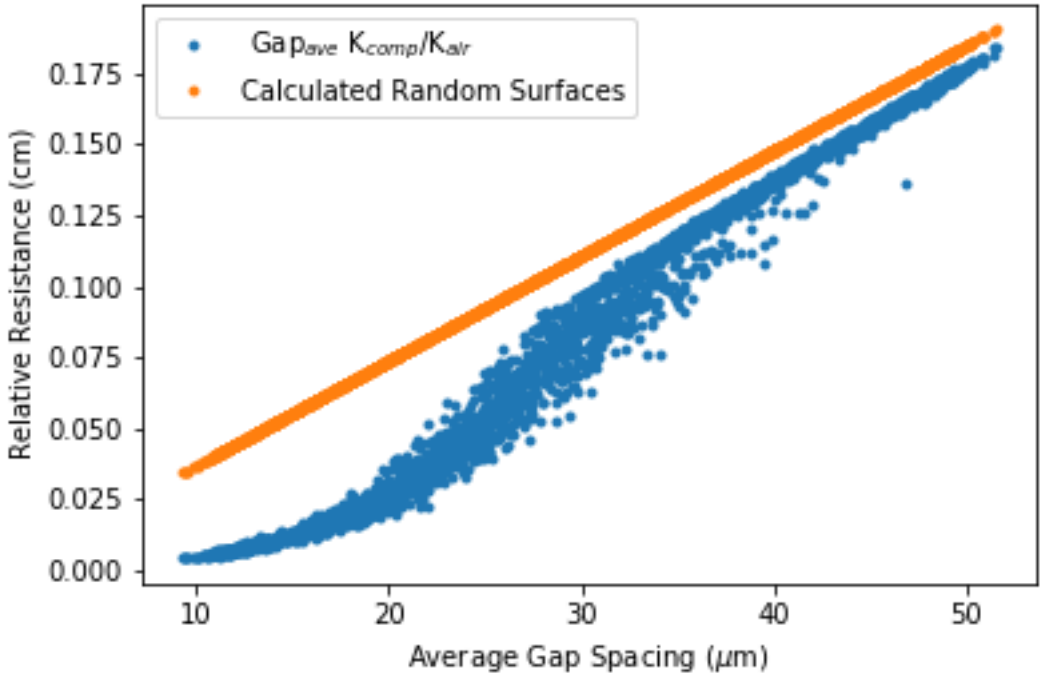
Vertical Profiles of Experimental Data and Simulation Data at 0.4 sec



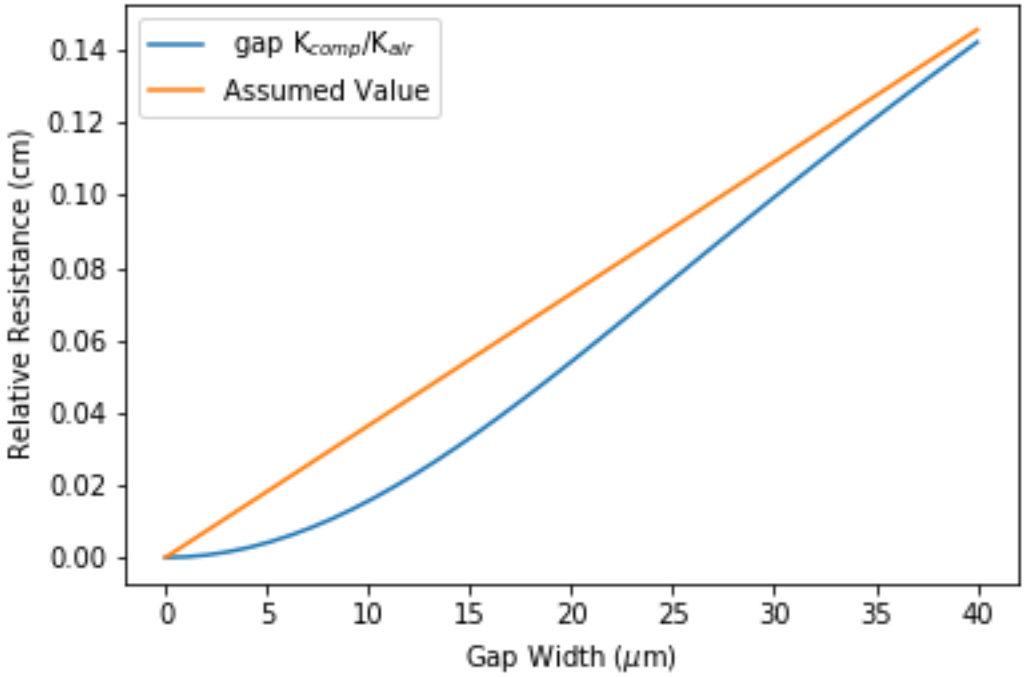


Delamination 0.36 cm from surface

Simulation of Variable Gap Spacing with Random Rough Surface

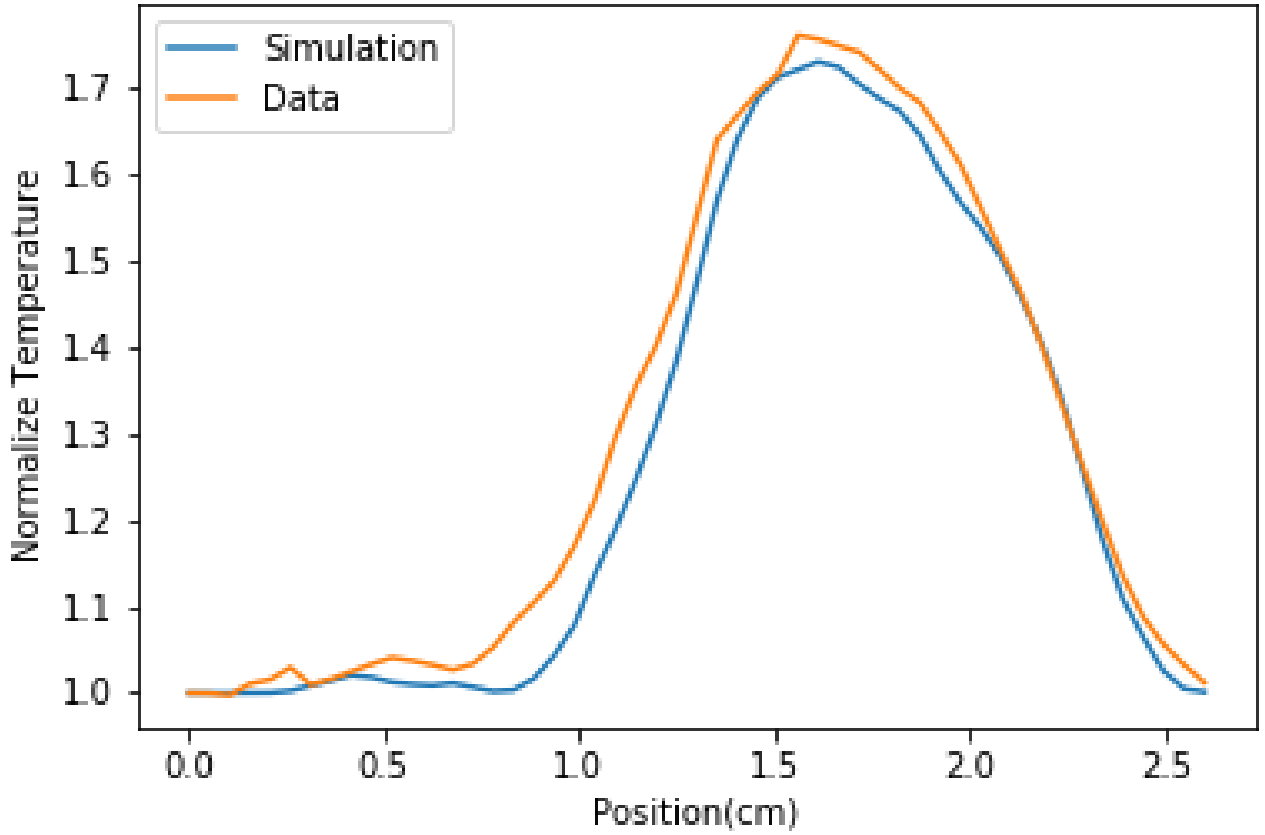


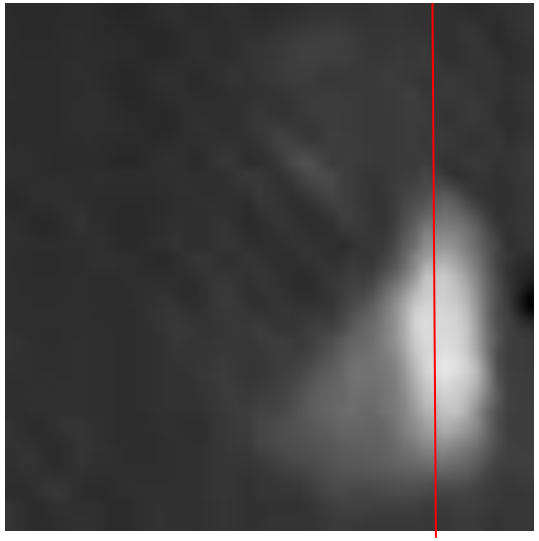
Results of 3000 simulations with random surface profiles at interface having standard deviation of 10 µm



Function dependence of average gap spacing and contact resistance used for simulations in following slides

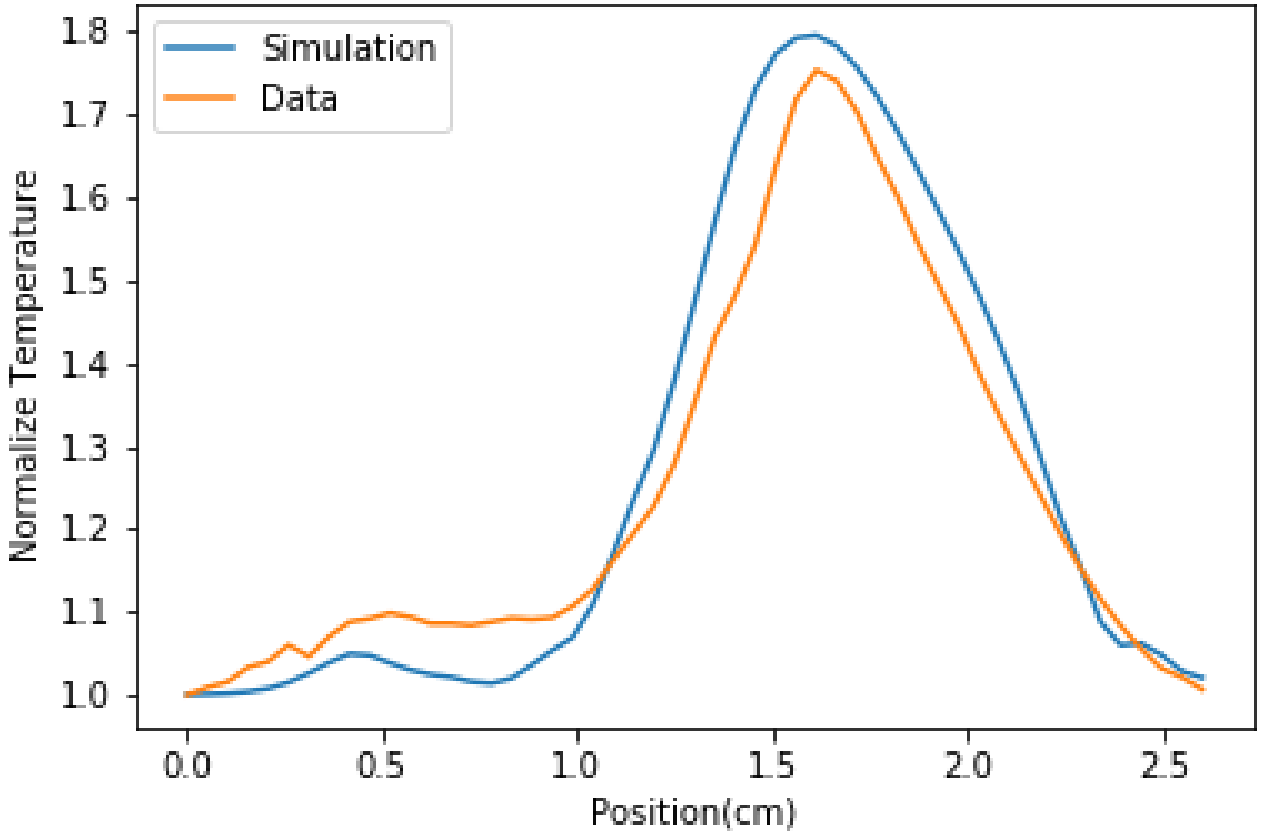
Vertical Profiles of Experimental Data and Simulation Data at 1/6 sec

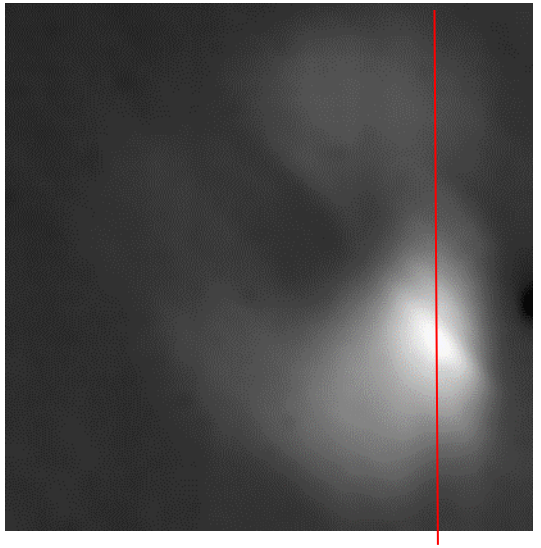




Delamination closest to surface

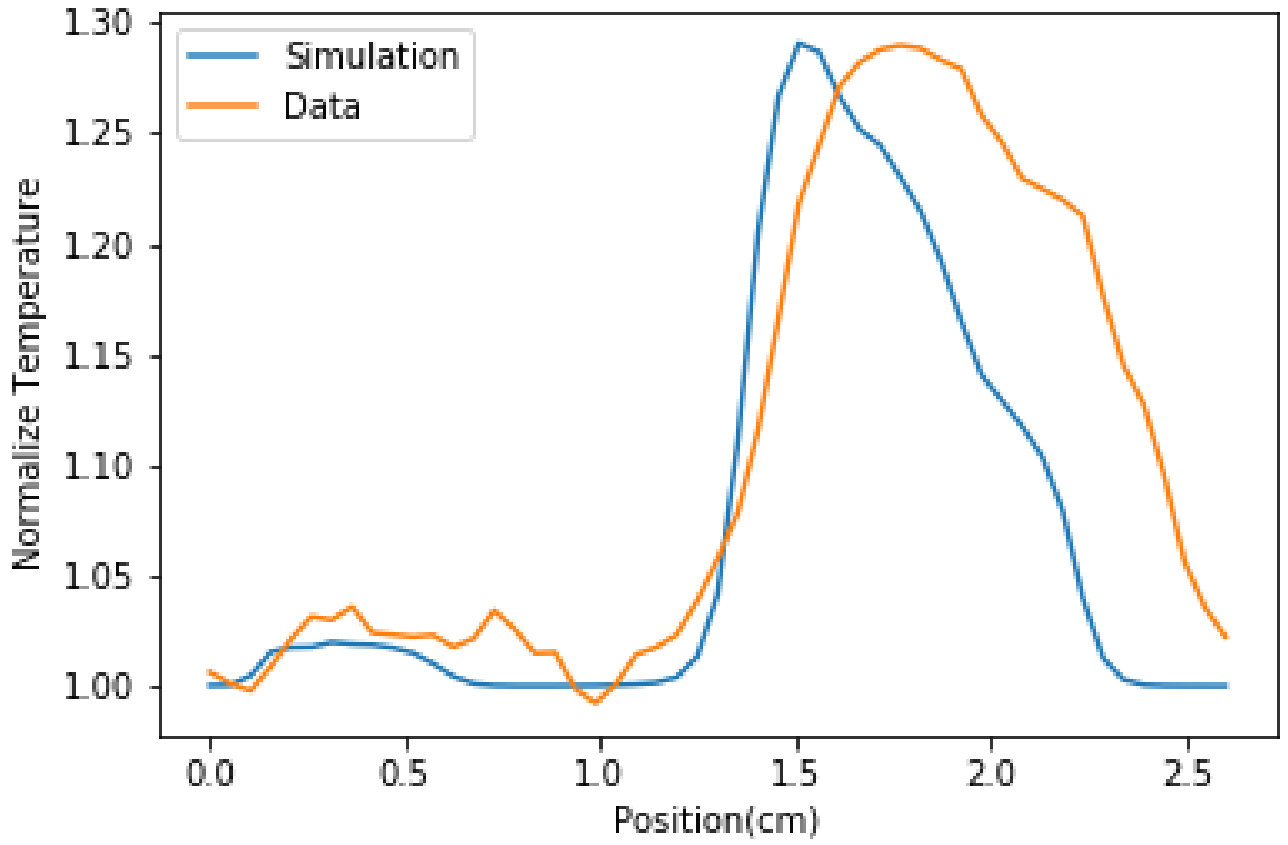
Vertical Profiles of Experimental Data and Simulation Data at 0.4 sec

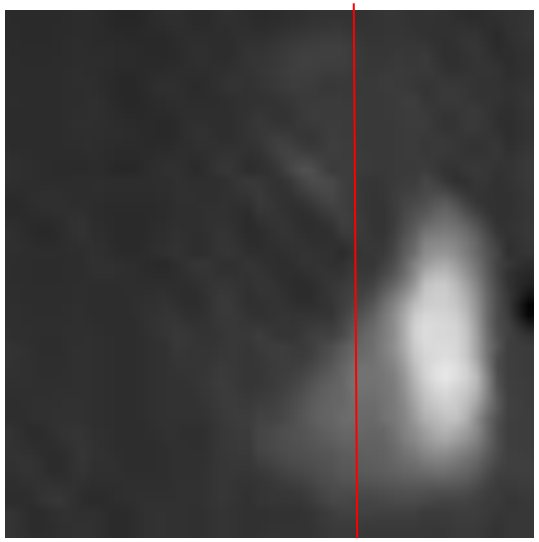




Delamination closest to surface

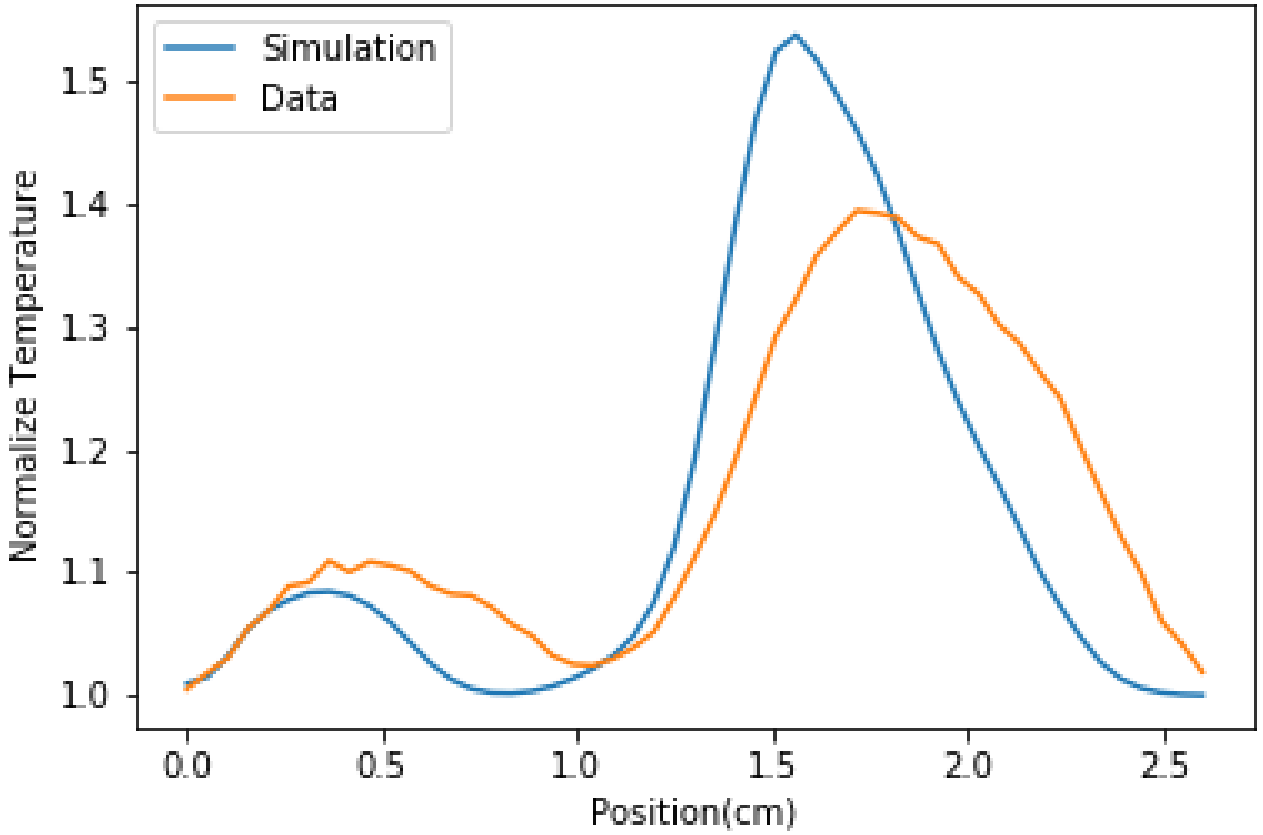
Vertical Profiles of Experimental Data and Simulation Data at1/6 sec

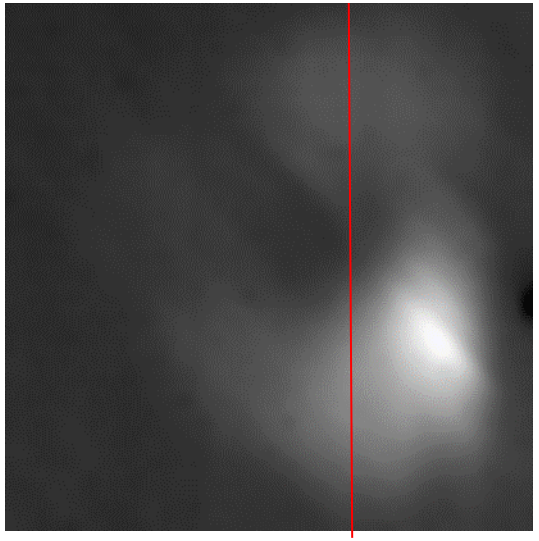




Delamination 0.36 cm from surface

Vertical Profiles of Experimental Data and Simulation Data at 0.4 sec





Delamination 0.36 cm from surface

Summary

- Small changes in contact resistance result in most significant changes in the contrast
- For the thermal properties of interest within the time frame of interest, large changes in in-plane diffusivity don't significantly change the contrast
- When using the K R estimated from CT and literature values for thermal conductivities, comparison of the absolute values of contrast between measurements and simulation is poor, particularly at times greater than 0.2 sec
- Using a K R estimated from CT that does not assume a linear relationship between gap thickness and contact resistance improves comparison