Realistic Thermographic Simulation of Impact Damage with Quadrupole Method

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Simulations assist in developing an understanding of the limitations of the technique and enable quantitative characterization of subsurface flaws.

Quadrupole Method is used for rapid simulation of thermographic inspection of composites.

This presentation:
- Examines the sensitivity of simulation to in-plane diffusivity and delamination contact resistance.
- Based on the computed tomography characterization of impact damage in a composite, simulates the thermal response.
- Compares the simulation results to experimental measurements.
- Iterates on contact resistance 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 composites
  - Previous methodology developed for single delamination at an interface between two layers
  - Methodology developed for multiple delaminations at multiple interfaces between layers and plates that are not aligned
    - Winfree, W., Zalameda, J. and Howell, P., Thermosense: Thermal Infrared Applications XLII; 114090K (2020)
For thin air gap, the thermal properties of the air gap can be represented by a contact resistance \( R \)

\[
R = \frac{d_{\text{gap}}}{K_{\text{air}}}
\]

In equations, \( R \) is always multiplied by thermal conductivity of layer, such that relevant term is \( K d_{\text{gap}}/K_{\text{air}} \)
Gap Thickness Influence on One-Dimensional Thermal Response

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

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 thick and 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 cm²/sec.

Air Gaps Widths

- 20 μm
- 30 μm
- 40 μm

Diameter of circular air gaps 1 cm
Block 4 x 4 x 0.2 cm
Aspect ratio (1,1,5)

Same scaling for all surface plots
Gap Width Influence on Three-Dimensional Thermal Response

First layer is 0.02 cm thick and the 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 cm²/sec and surface normal diffusivity is 0.005 cm²/sec.

Air Gaps Widths

Diameter of circular air gaps 1 cm
Block 4 x 4 x 0.2 cm
Aspect ratio (1,1,5)

Same scaling for all surface plots
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 cm²/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 cm²/sec
In-plane diffusivity 0.025 cm²/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 responses reflect the shape of the wedge
Increasing in-plane diffusivity by a factor of 5 does not dramatically change response
Composite has 18 plies.
From CT data, delaminations were present at 13 different depths.
Most Depths have two significant delaminations.
Impact Damage has the typical "petal" appearance.

Different Color for each depth

First three depths:
- Red 0.0178 cm
- Green 0.0347 cm
- Blue 0.0532 cm

Volume: 3.2 cm by 3.2 cm by 0.332 cm
Aspect ratio: 1:1:8

View from top:
Area: 3.2 cm by 3.2 cm
CT Data Through an Impacted Region of the Composite

Delaminations are not flat

Gap width not the same for all delaminations

Contrast between delamination and composite indication of gap width
This contrast is used to estimate the gap width of the delamination
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
CT Images and Estimated Gap Spacing

All CT images scaled the same
All of the gap spacing scaled from 0 to 0.050 mm
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 \( \sim 50 \, \mu m \)
- Thermal conductivity composite: 97000 Erg/(cm K sec)
- Surface normal diffusivity: 0.0044 cm\(^2\)/sec
- In-plane diffusivity: 0.001 cm\(^2\)/sec
- Thermal conductivity of air: 2624 Erg/(cm K sec)
- Largest \( K_{\text{composite}} \) R is \( \sim 0.18 \) cm
Comparison of Flash Thermography Simulation of Impacted Composite and Measured Response

Images:
- Measured Response
- Simulation Results

- Images 3.2 by 3.2 cm
- Areas with thinner gap widths tend to fade faster in measurement than simulation

Timepoints:
- 0.1 sec
- 0.2 sec
- 0.4 sec
- 0.8 sec
Horizontal Profiles of Experimental Data and Simulation Data

- Reasonable agreement early times
- Poor agreement at later times

Quad - Simulation data
Exp - Experimental data
Vertical Profiles of Experimental Data and Simulation Data

Reasonable agreement early times
Poor agreement at later times

Delamination 0.178 cm from surface
Delamination 0.178 cm from surface
Delamination 0.532 mm from surface

Quad - Simulation data
Exp - Experimental data
Vertical Profiles of Experimental Response and Simulation Results for $\frac{1}{2}$ K R Value Estimated from CT

Much better agreement assuming K R is $\frac{1}{2}$ value estimated from CT

Quad - Simulation data
Exp - Experimental data
Vertical Profiles of Experimental Response and Simulation Results for \( \frac{1}{2} K R \) Value Estimated from CT

Much better agreement assuming \( K R \) is \( \frac{1}{2} \) value estimated from CT.
Comparison of Flash Thermography Simulation When KR Reduced by Factor of Two

Absolute values are considerably better, however, contrast images are not dramatically different.
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 $\frac{1}{2}$ the $K_R$ estimated from CT and literature values for thermal conductivities, comparison of the absolute values of contrast between measurements and simulation is reasonable