

Least Squares Reverse Time Migration (LSRTM) for Damage Imaging in Composite Laminates

Jiaze He^{1*}, Anthony Schwarberg¹, John D. Day¹, Erik Frankforter²

¹ Department of Aerospace Engineering and Mechanics, University of Alabama, Tuscaloosa,
AL, USA

² NASA Langley Research Center, Hampton, VA, USA

Outline

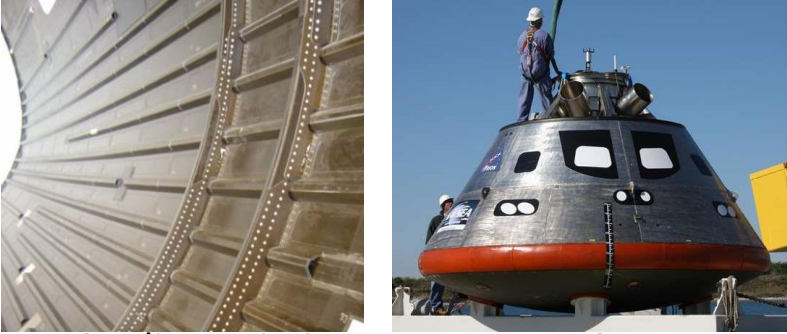
- Motivation
- Overview of LSRTM for metallic materials
- Cases Studies of LSRTM for composite laminates
 - 1) Resolution Studies
 - 2) Multiple damage sites with different scatter amplitudes
 - 3) Multiple damage sites with different dimensions
 - 4) Complex damage shapes
- Conclusion

Outline

- Motivation
- Overview of LSRTM for metallic materials
- Cases Studies of LSRTM for composite laminates
 - 1) Resolution Studies
 - 2) Multiple damage sites with different scatter amplitudes
 - 3) Multiple damage sites with different dimensions
 - 4) Complex damage shapes
- Conclusion

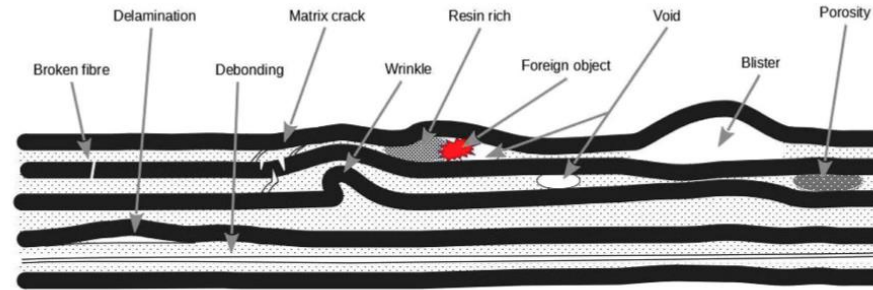
Complexities in Ultrasonic NDE and SHM

Structural Complexity



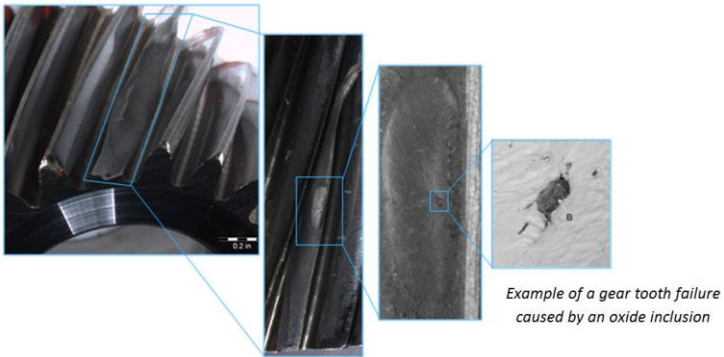
Credits: Aviationspectator, NASA

Material and Damage/Defects Complexity

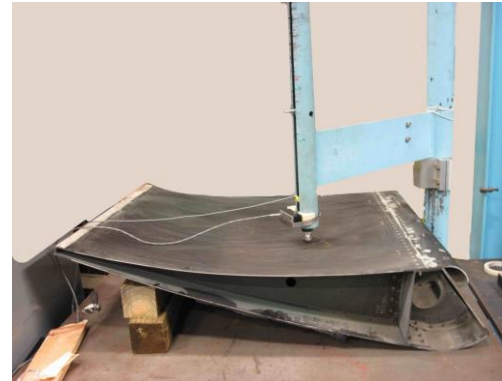


Credits: Engineering360

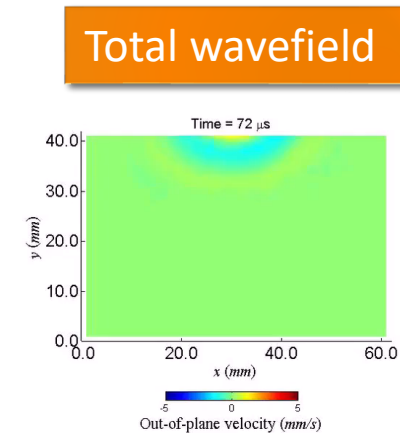
A sandwich composite aileron part in a drop-ball test



Credits: TimkenSteel



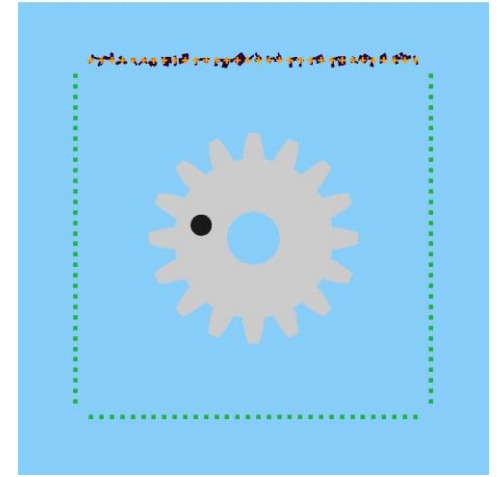
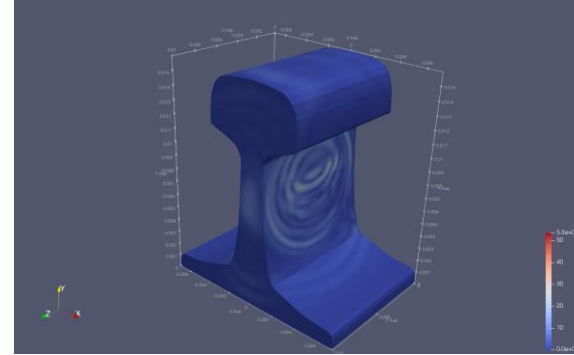
Used by Air Force for the Aircraft Structural Integrity Program (ASIP)



Motivation of Computational Imaging Methods

Addressing complexities

- Forward modeling for complex structures
- Imaging algorithm utilizes reflected, refracted, and diffracted waves



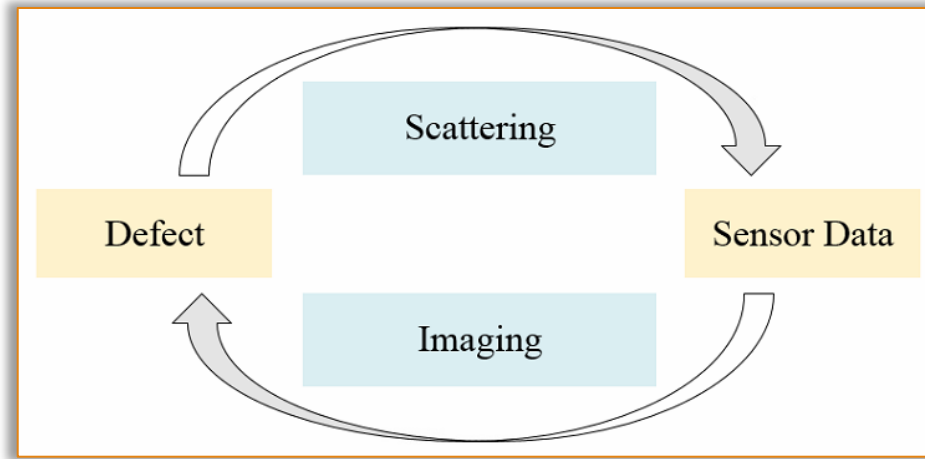
Performance Evaluation/optimization of novel inspection or monitoring methods

Objective: Develop a high-resolution imaging method for composite laminates based on a least-squares reverse-time migration (LSRTM) algorithm using ultrasonic guided waves.

Outline

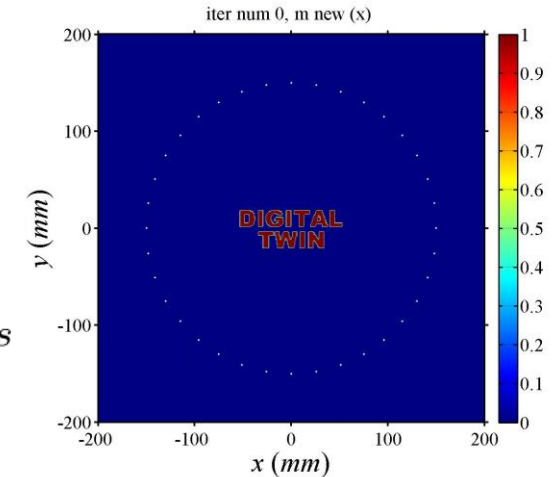
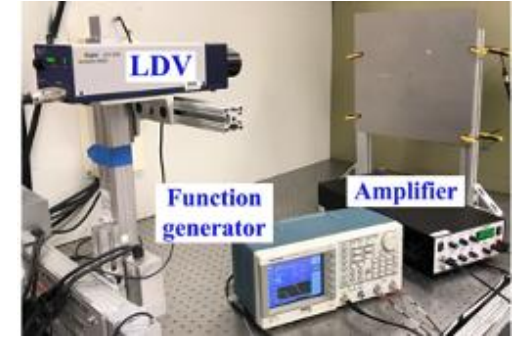
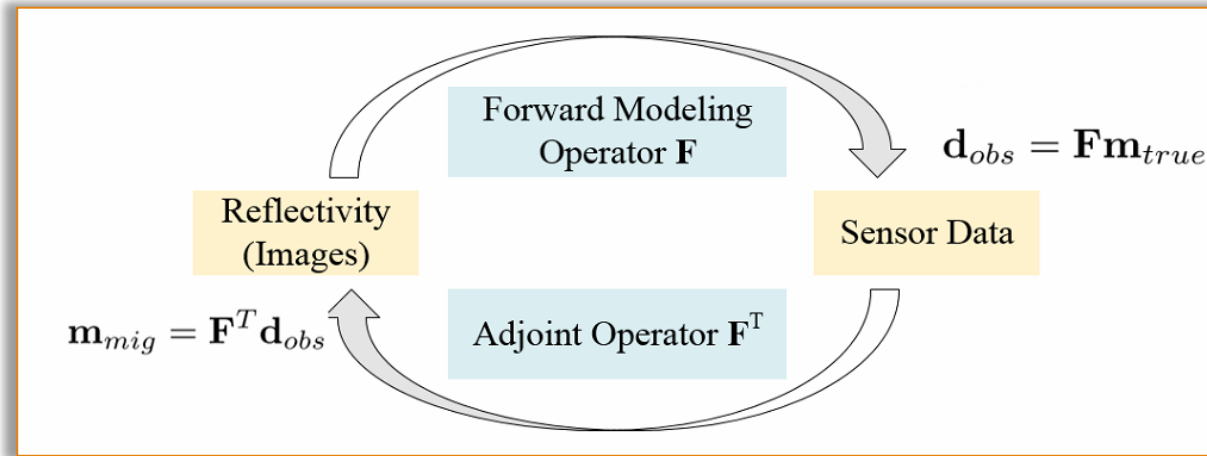
- Motivation
- Overview of LSRTM for metallic materials
- Cases Studies of LSRTM for composite laminates
 - 1) Resolution Studies
 - 2) Multiple damage sites with different scatter amplitudes
 - 3) Multiple damage sites with different dimensions
 - 4) Complex damage shapes
- Conclusion

Damage imaging scheme



LSRTM scheme

- An inversion-based method



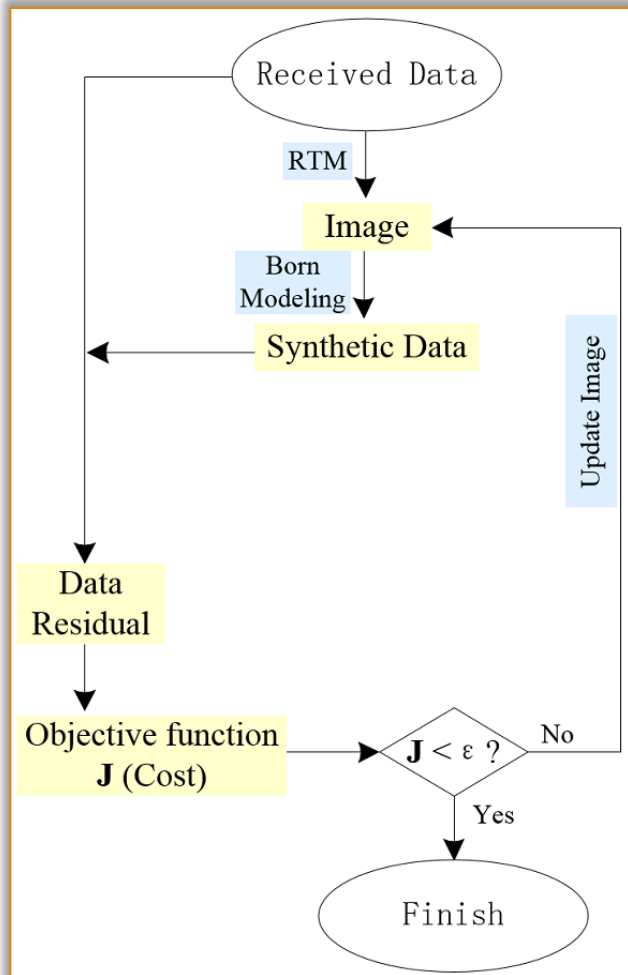
Conventional Migration $\mathbf{m}_{mig} = \mathbf{F}^T \mathbf{d}_{obs}$

Inversion $\mathbf{m}_{true} = (\mathbf{F}^T \mathbf{F})^{-1} \mathbf{m}_{mig} = (\mathbf{F}^T \mathbf{F})^{-1} \mathbf{F}^T \mathbf{d}_{obs}$

Minimizing a cost function $\mathcal{J} = \sum_e \frac{1}{2} \|\mathbf{d}_{obs} - \mathbf{F}\mathbf{m}\|^2$

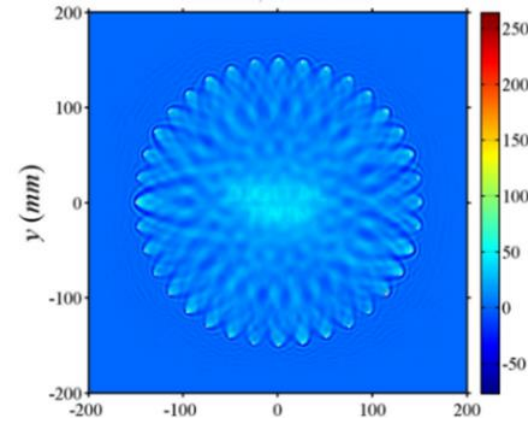
Conjugate gradient method for least-square reverse-time migration

Flow chart for LSRTM



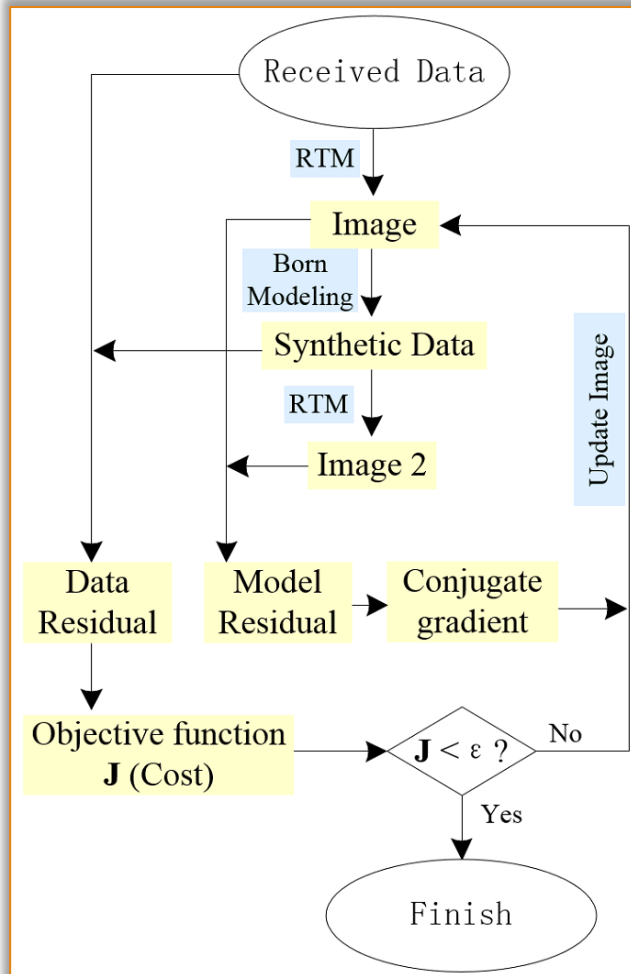
Conventional RTM

RTM – (Aluminum Plate)



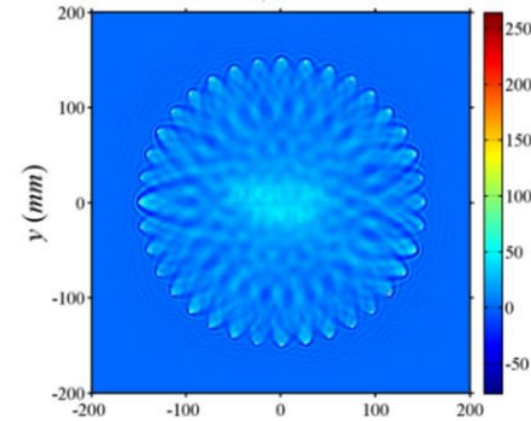
Flow chart for LSRTM

Add citations



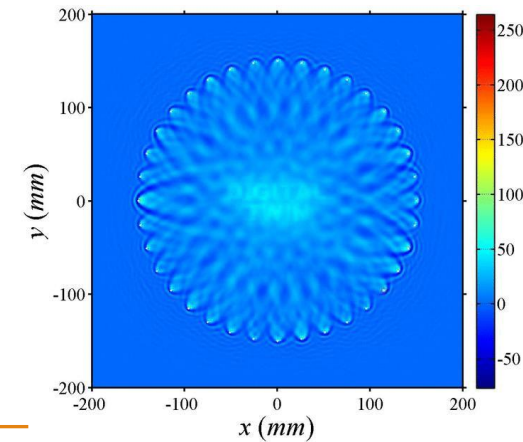
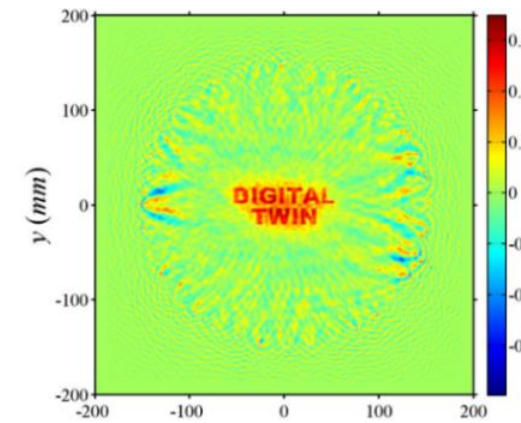
Conventional RTM

RTM – (Aluminum Plate)



LSRTM

LSRTM (Aluminum Plate)

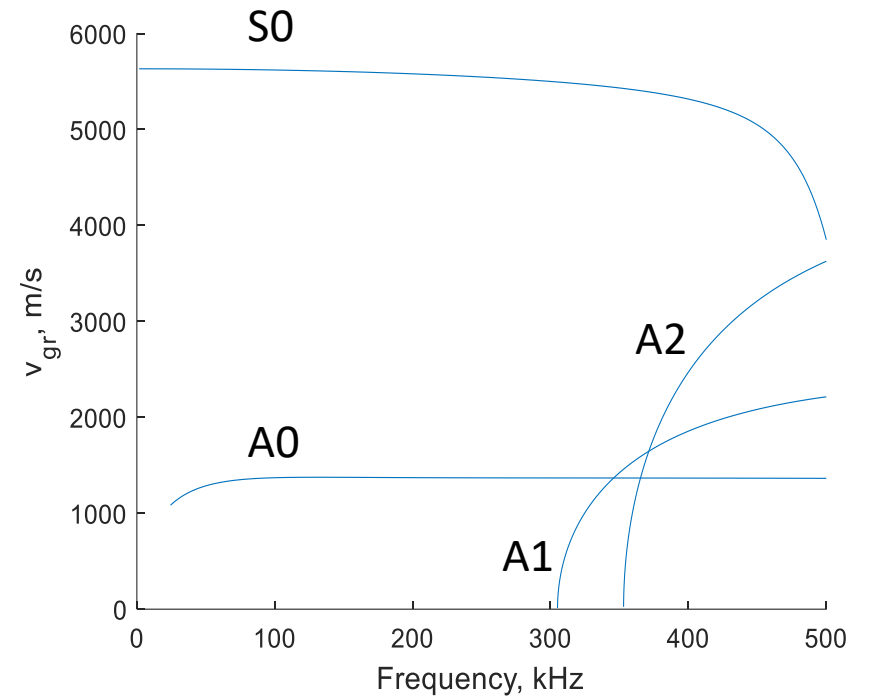


Outline

- Motivation
- Overview of LSRTM for metallic materials
- Cases Studies of LSRTM for composite laminates
 - 1) Resolution Studies
 - 2) Multiple damage sites with different scatter amplitudes
 - 3) Multiple damage sites with different dimensions
 - 4) Complex damage shapes
- Conclusion

Simulation Parameters

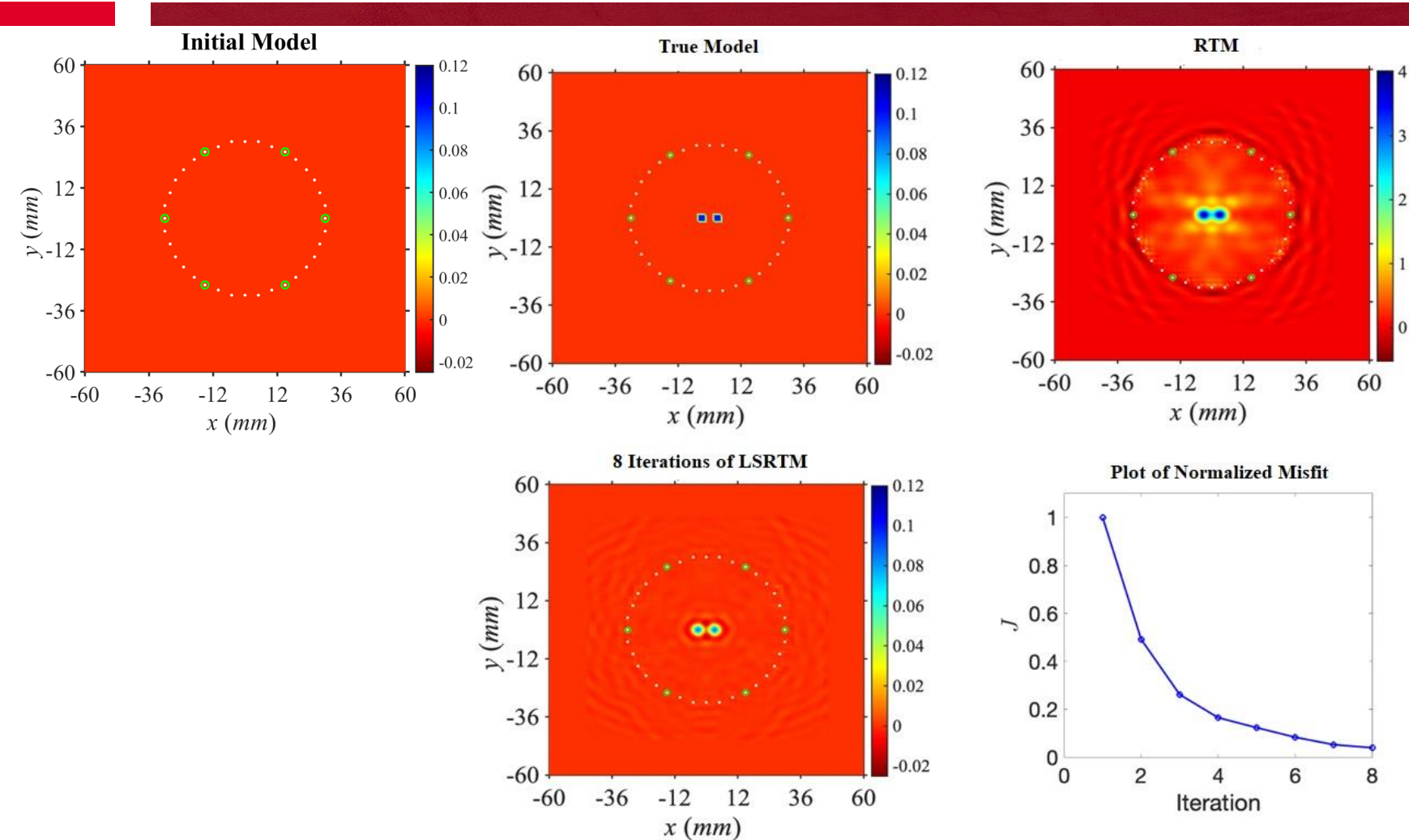
- Excitation frequency: 100 kHz
- Grid mesh: 1 mm x 1mm
- 36 sensors
- 6 actuators
- 16-layer laminate plate
- $[45/-45/0/0]_{2s}$
- Graphite/epoxy IM-6/3501-6
- Excitation frequency below higher order modes (< 300 kHz)
- A0 wavelength: 10.2 mm at 100 kHz
 - ~ 10 discretization per wavelength



Lamina Properties for graphite/epoxy IM-6/3501-6

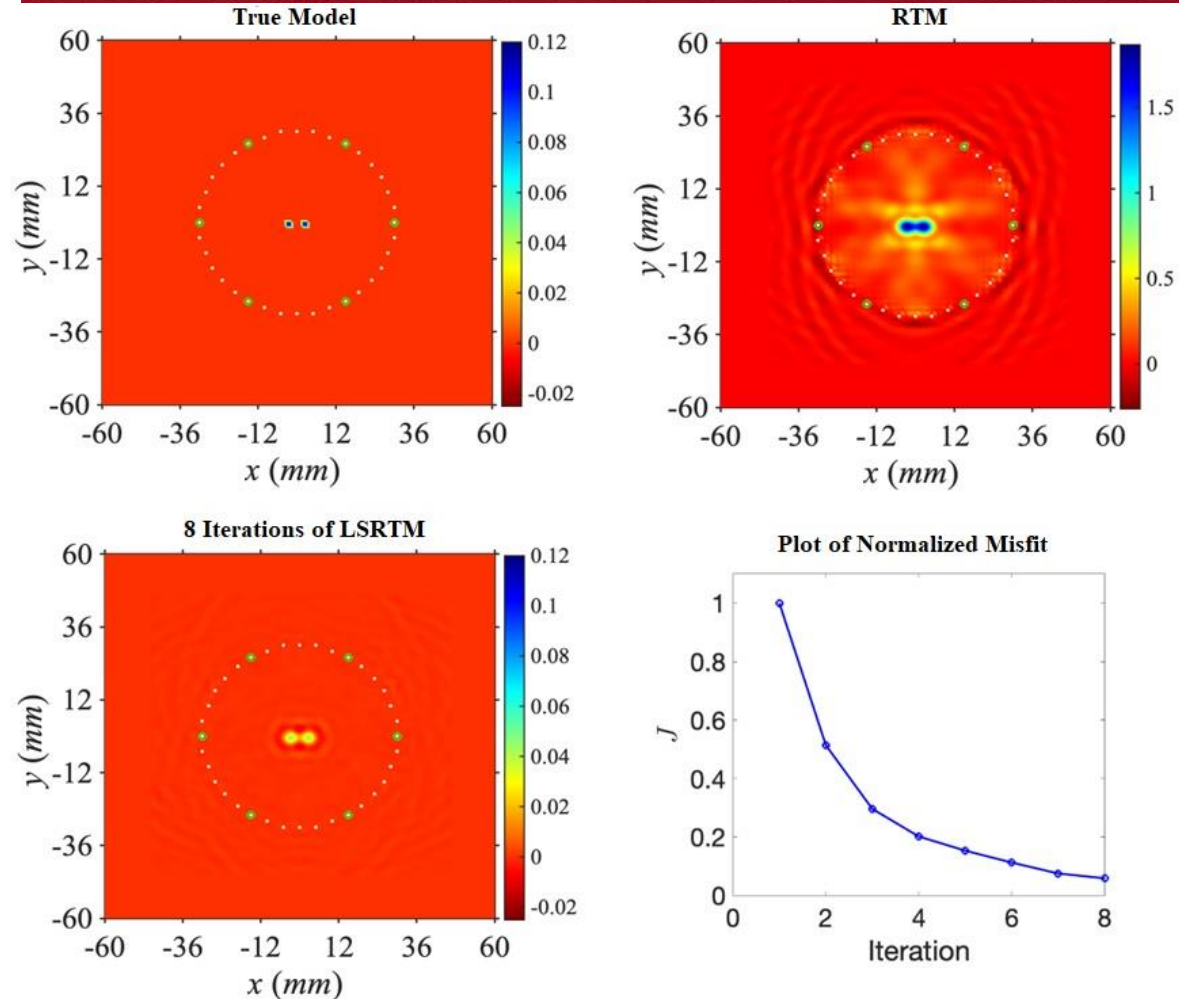
E_{11} (GPa)	E_{22} (GPa)	E_{33} (GPa)	G_{12} (GPa)	G_{13} (GPa)	G_{23} (GPa)	ν_{12}	ν_{13}	ν_{23}	ρ (kg/m ³)
127.6	11.3	11.3	5.97	5.97	3.75	0.30	0.30	0.34	2700

Resolution Case with 2 mm Side Lengths



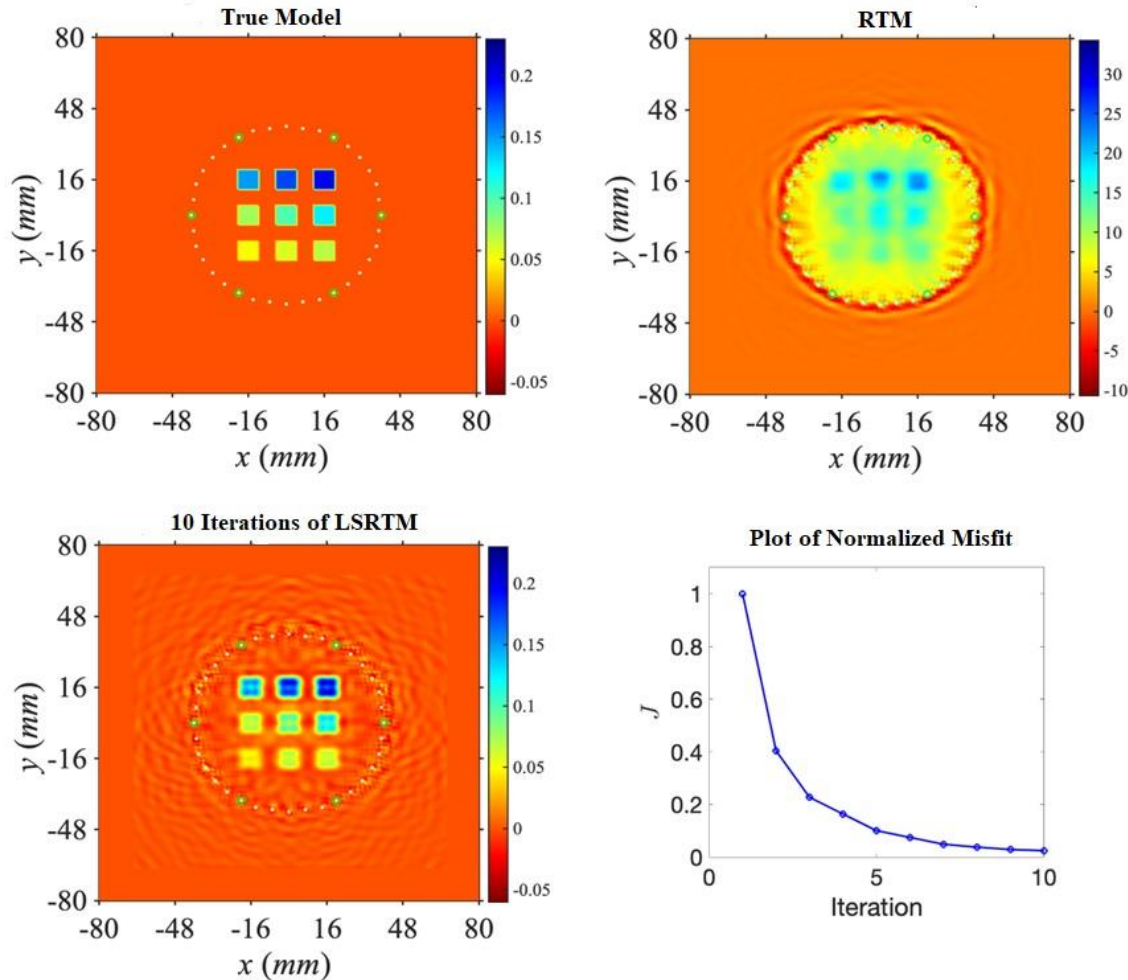
- Square side lengths: 2 mm
 - Spacing between damage sites: 4 mm
 - Reflectivity amplitude: 0.1
 - Domain size: 121 mm x 121 mm
-
- LSRTM image show separation between damage sites and reduces distortion

Resolution Case with damage 1 mm Side Lengths



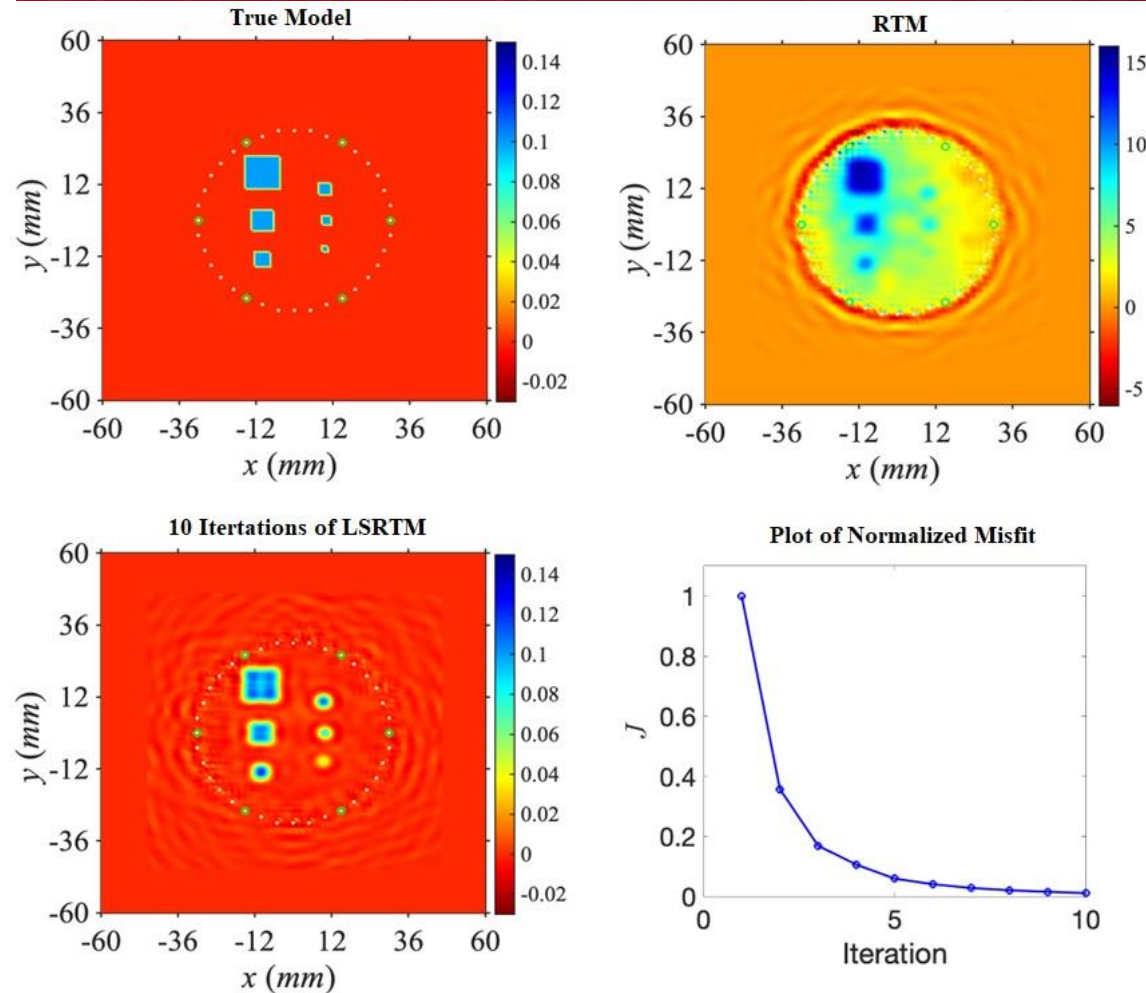
- Square side lengths: 1 mm
 - Spacing between damage sites: 4 mm
 - Reflectivity amplitude: 0.1
 - Domain size: 121 mm x 121 mm
-
- LSRTM is able to discern two damage sites, unlike RTM, however the reflectivity amplitude is incorrect

Multiple Damage Sites with Different Reflectivity

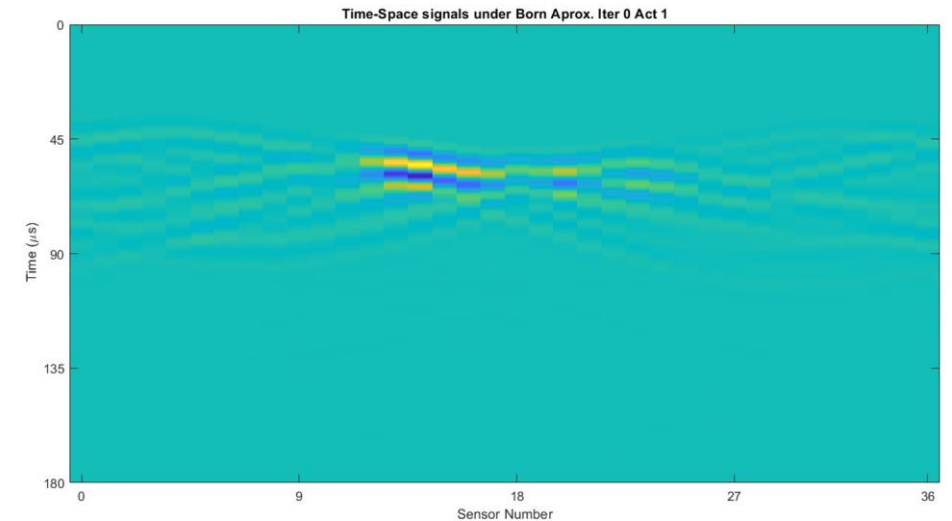


- Square side lengths: 8 mm
 - Spacing between damage sites: 8 mm
 - Reflectivity amplitudes: 0.05, 0.06, 0.07, 0.075, 0.1, 0.125, 0.15, 0.175, 0.2
 - Domain size: 161 mm x 161 mm
-
- LSRTM clearly defines the shape of each damage site and is able to accurately predict the reflectivity amplitude at each site

Multiple Damage Sites with Different Dimensions

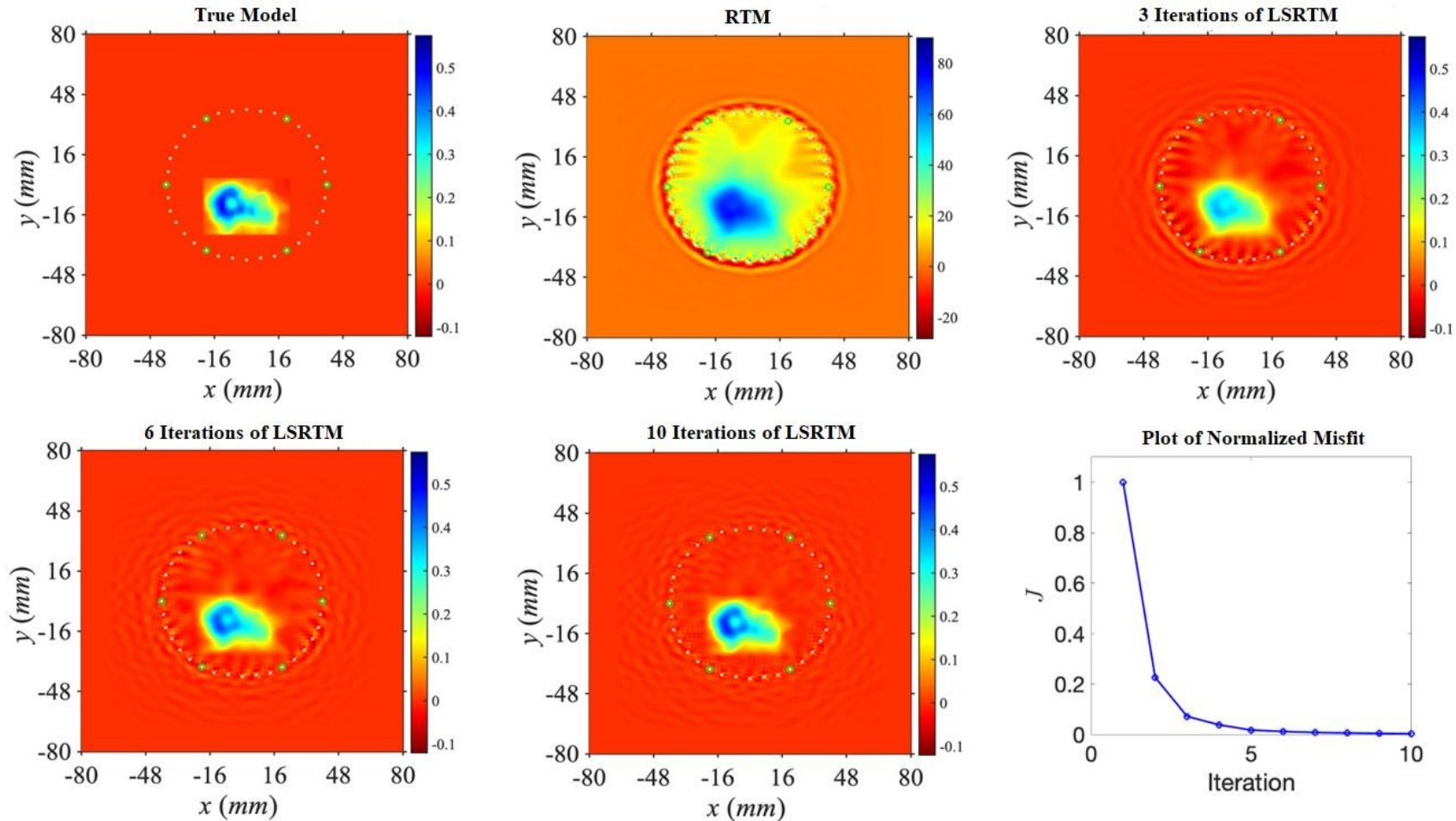


- Square side lengths: 10, 6, 4, 3, 2, and 1 mm
- Reflectivity amplitude: 0.1
- Domain size: 121 mm x 121 mm



- LSRTM is able to detect the smallest damage sites and clearly define the shape of the largest damage sites, unlike RTM.

Complex Damage



- Domain size: 161 mm x 161 mm

- After 10 iterations, LSRTM produces an image that is nearly identical to the true model, whereas RTM only produces a distorted outline of the image

Elastodynamic Solver run for Cross-Verification

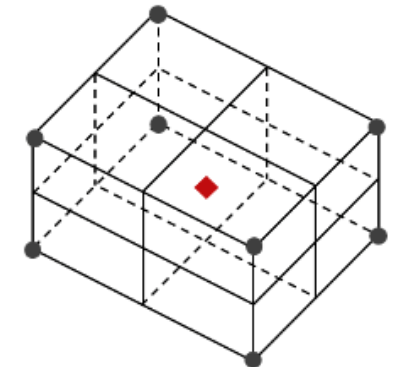
- Mindlin plate solver used for imaging compared with rotated staggered grid (RSG) finite difference solver
 - RSG solver open-sourced by NASA Langley
<https://github.com/nasa/PanNDE>
 - RSG solver previously validated for multiple composites plates (e.g. quasi-isotropic, cross-ply with and without delamination)
- Same parameters as before, except for discretizations:
 - $dx=dy= 0.75$ mm, ~ 13.6 discretizations per shortest A_0 wavelength
 - 3 discretizations per ply in the thickness-direction

Stress-velocity
elastodynamic equations:

$$\rho \partial_t v_i = \partial_{x_j} \sigma_{ij} + f_i^v$$

$$\partial_t \sigma_{ij} = c_{ijkl} \partial_{x_l} v_k + f_{ij}^\sigma$$

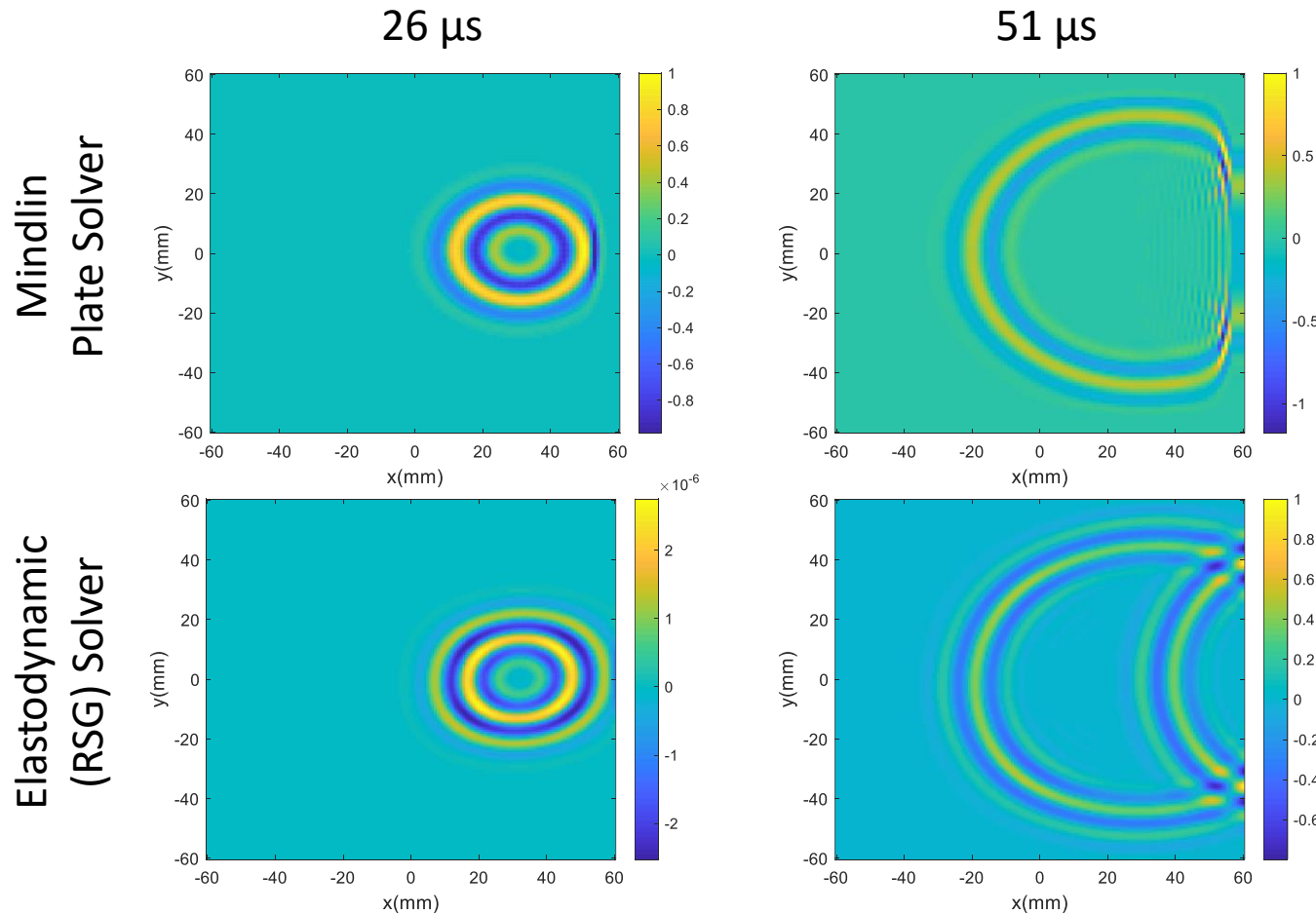
RSG Unit Cell:



◆ $\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \tau_{xz}, \tau_{yz}, \tau_{xy}$

● v_x, v_y, v_z

Pristine specimen guided wave comparisons



- Little-to-no in-plane dominant S_0 mode energy observed in RSG solver (which Mindlin plate model cannot resolve)
- RSG solver improved predictions of directional group velocity variation and lateral edge reflection

	$v_{gr}, 0^\circ$	% Error	$v_{gr}, 90^\circ$	% Error
Mindlin Plate Solver	1222 m/s	-10.9%	1222 m/s	-1.1%
RSG Elastodynamic Solver	1457 m/s	6.3%	1245 m/s	0.7%
DISPERSE	1371 m/s	-	1236 m/s	-

Conclusion

- We have proposed an ultrasonic guided wave damage imaging method for composite laminates using LSRTM
- LSRTM reduces artifacts
- LSRTM damage images are less distorted than RTM images
- LSRTM more accurately captures changes in reflectivity amplitude compared to RTM
- LSRTM has shown promising resolution

Future work: add experimental work and conduct more comparative studies using solvers that are widely used.

Thank you for your attention!

- Jiaze He Email: jhe26@eng.ua.edu