

Simulation of Detecting Damage in Composite Stiffened Panel Using Lamb Waves

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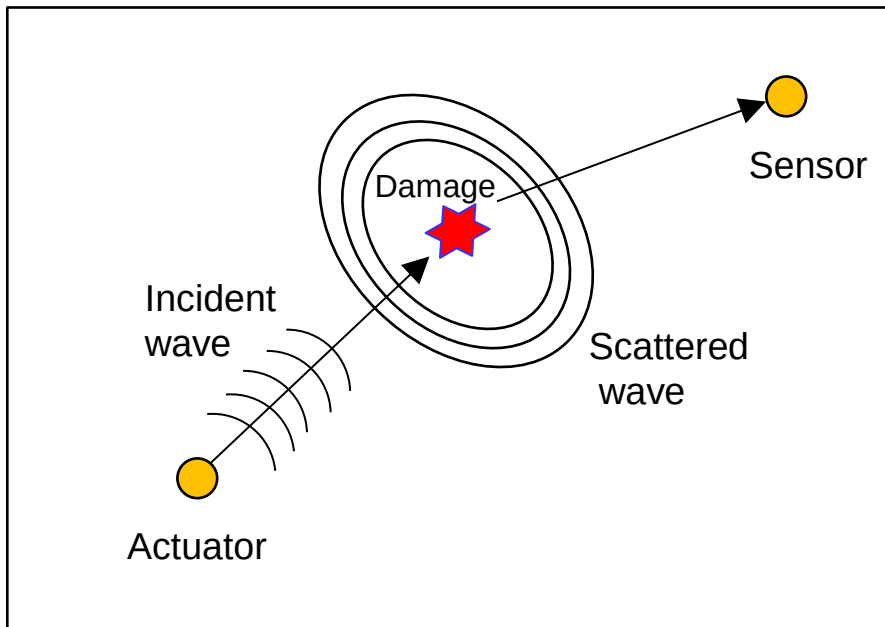
Technical Specialists' Meeting on Rotorcraft Structures and Survivability

October 29-31, 2013

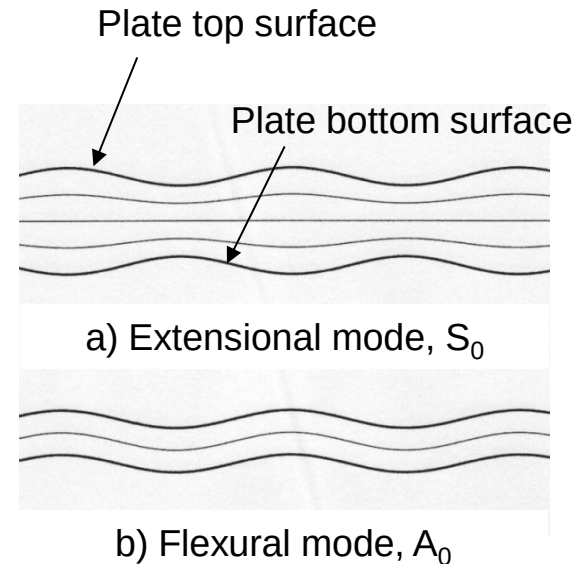
Ft. Magruder Hotel and Conference Center, Williamsburg, VA

Introduction

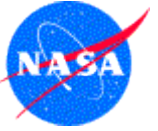
- Lamb wave (guided wave) can be used to detect damage at a long distance in plate-like structure
- Lamb waves are dispersive and their propagation speeds are frequency dependent



Lamb wave damage detection

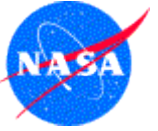


Zero-order Lamb wave modes



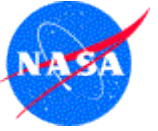
Motivation

- Simulations are needed for understanding the dispersive nature of Lamb waves, evaluating the effect of structural configurations, determining actuator/sensor placements, and interpreting Lamb wave damage detection results
- It is desirable to use a damage imaging technique that is computationally efficient to get results in real time



Objectives

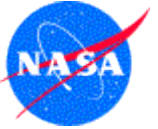
Investigate the potential of using an efficient damage imaging technique for damage identification by using a commercial finite element code to simulate the Lamb wave propagation in stiffened composite structures



Outline

- Methods for simulating damage detection
- Efficient damage imaging technique
- Models and simulation setup for pristine and damaged composite stiffened panels
- Simulation of Lamb wave damage detections
 - Case 1: Skin-bay damaged panel
 - Case 2: Flange/skin debond panel
- Concluding remarks

Methods for Simulating Damage Detection

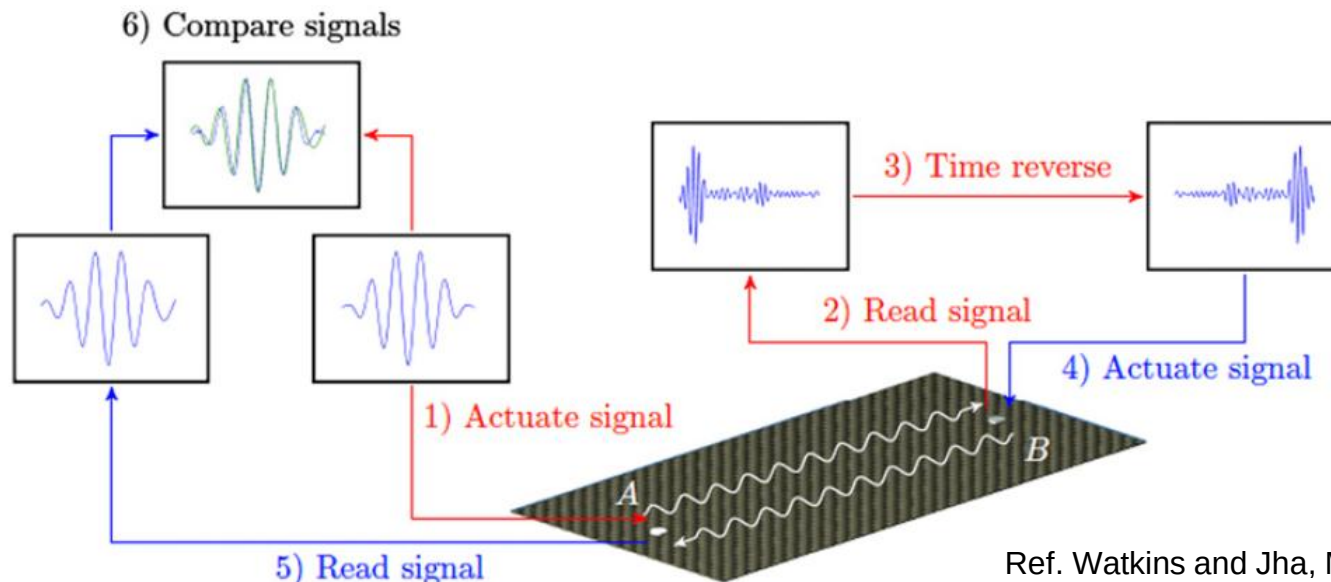


1. Finite element analysis method

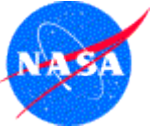
2. Time reversal method

3. Image condition

Zero-lag cross-correlation (ZLCC) of incident wave signal and time reversal signal



Efficient Damage Imaging Technique

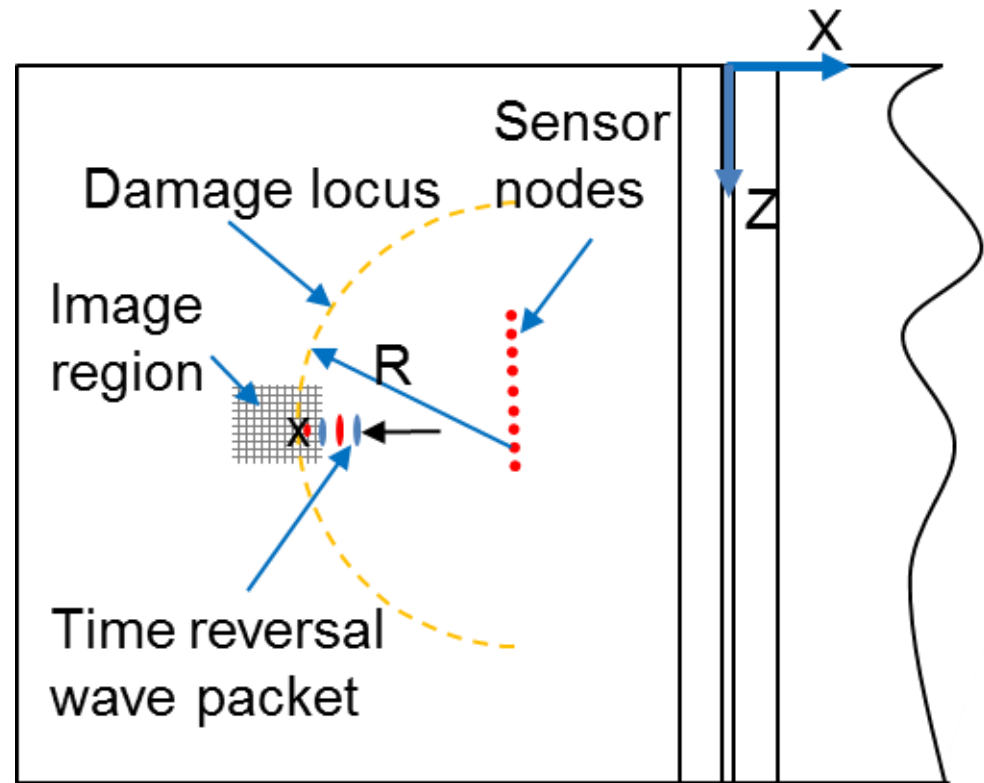


Determine damage locus
($R = C_g \times \text{TOF}$)

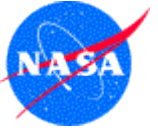
Determine the path of
time reversal wave
packet

Estimate the intersection
point (X) and apply **image
condition to compute
ZLCC values at neighboring
finite element nodes**

Estimate the damage size
based on the computed
ZLCC values



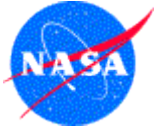
C_g : Group velocity
TOF : Time of flight



Outline

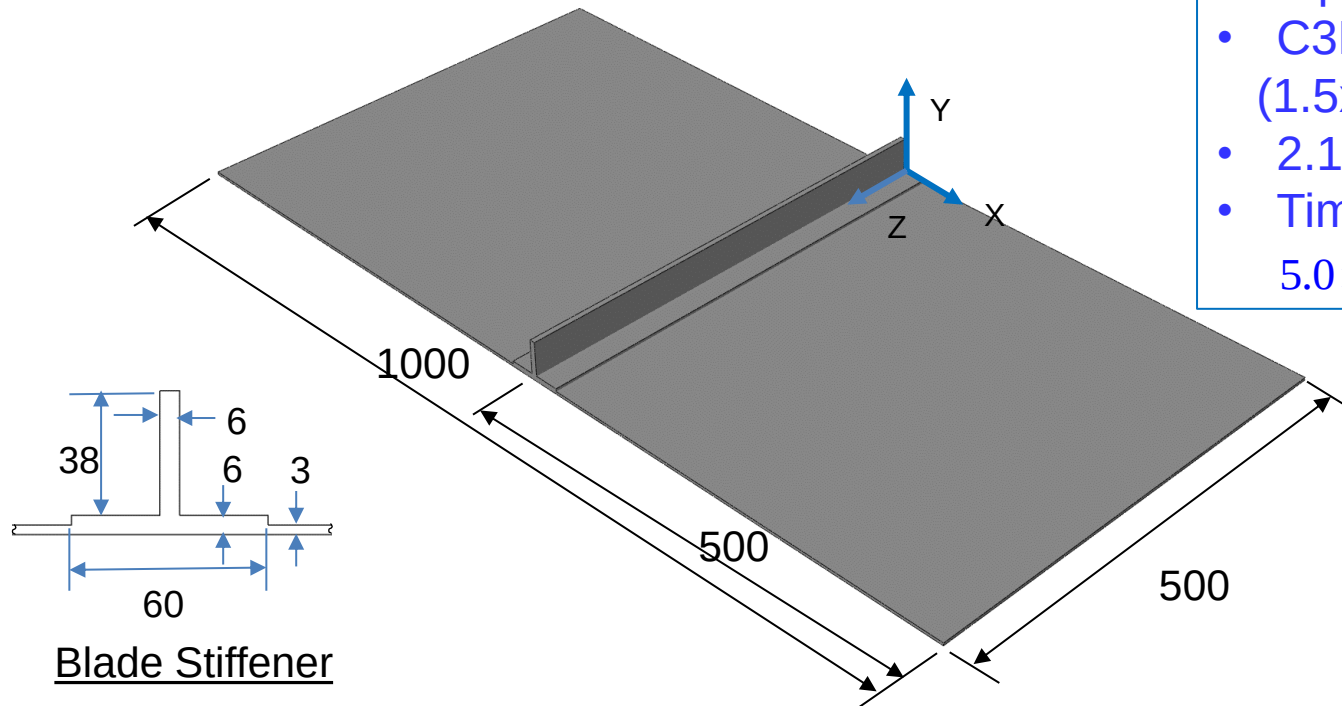
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Model for Pristine Composite Stiffened Panel



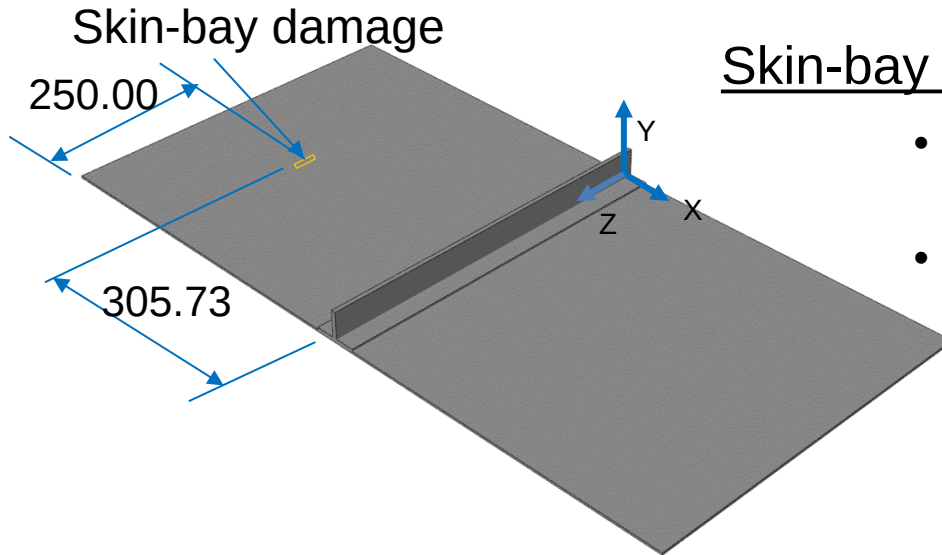
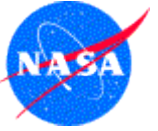
Abaqus/Explicit Code

- C3D8R element (1.5x1.5x1.5 mm)
- 2.1 million DoFs
- Time step: 5.0×10^{-8} sec



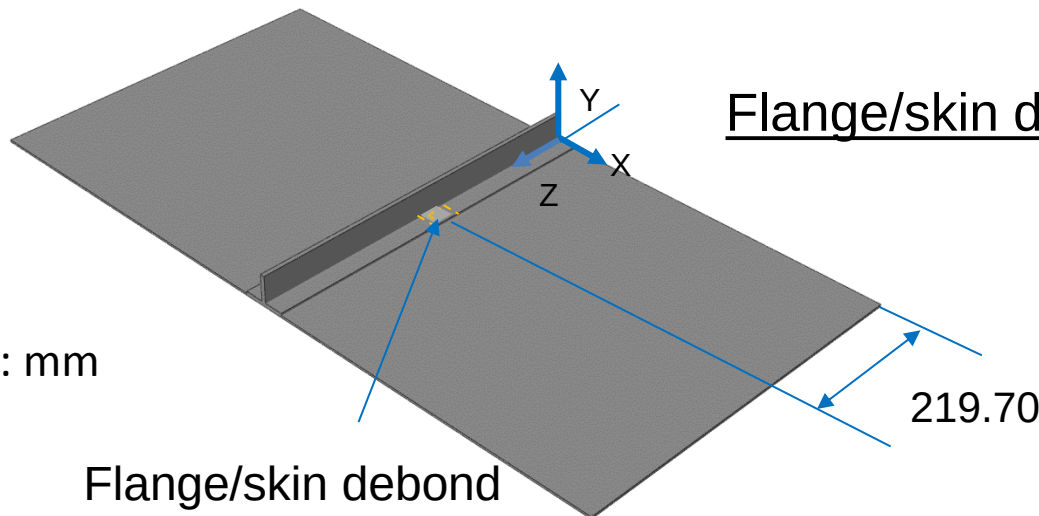
- Unit: mm
- Material: IM7/8552 laminates
- Quasi-isotropic lay-ups for skin, blade, and flange (using equivalent 3D properties)
- Free boundary conditions for the plate

Models for Damaged Composite Stiffened Panel



Skin-bay damaged panel

- Rectangular damage: 3.13 mm x 30.30 mm
- 90% reduction of material properties in the damaged region)

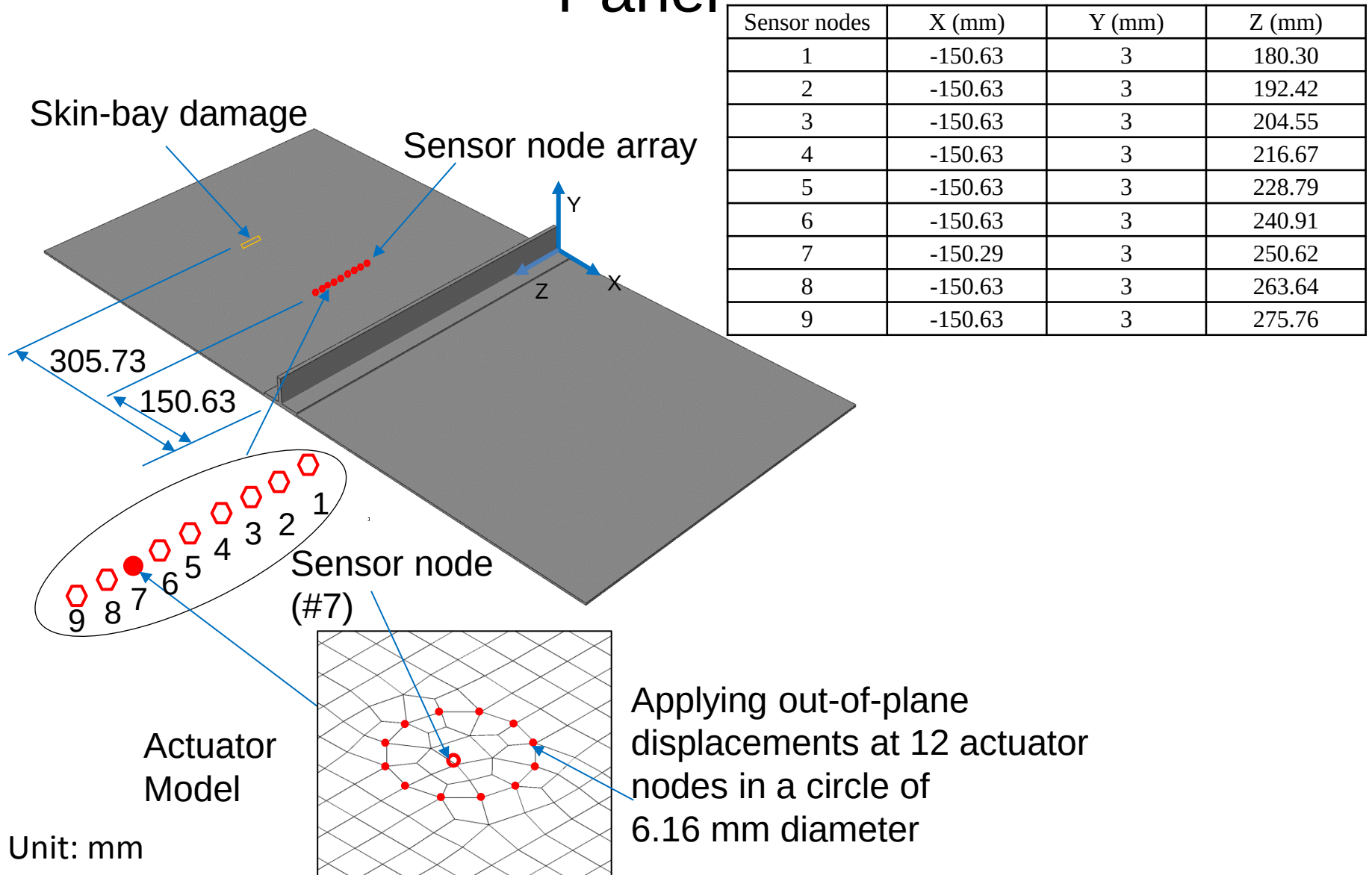


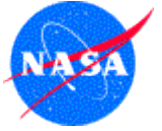
Flange/skin debond panel

- Debond width: 30.30 mm
- Double nodes in the debond area
- Contact not modeled

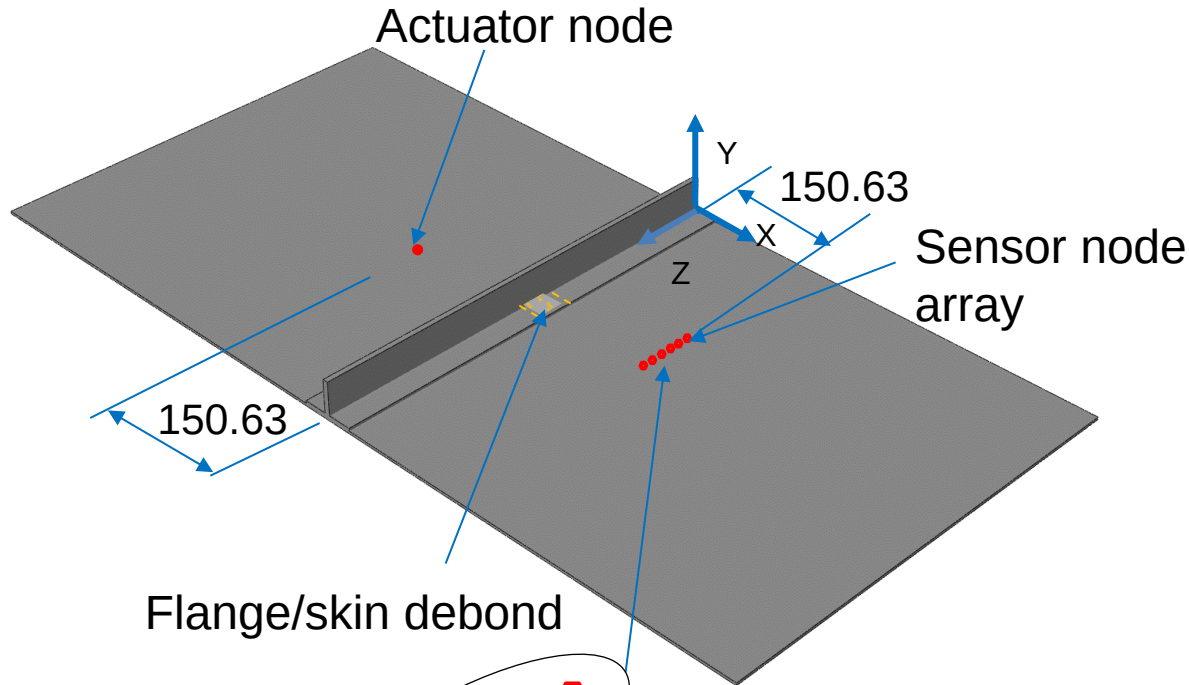
Unit: mm

Simulation Setup for Skin-bay Damaged Panel

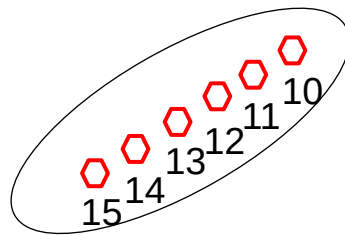




Simulation Setup for Flange/Skin Debond Panel



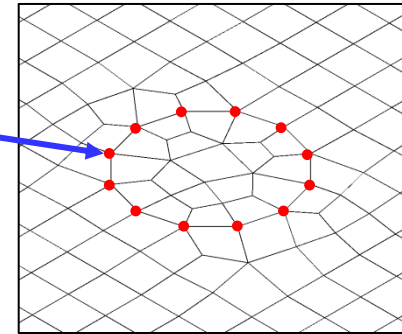
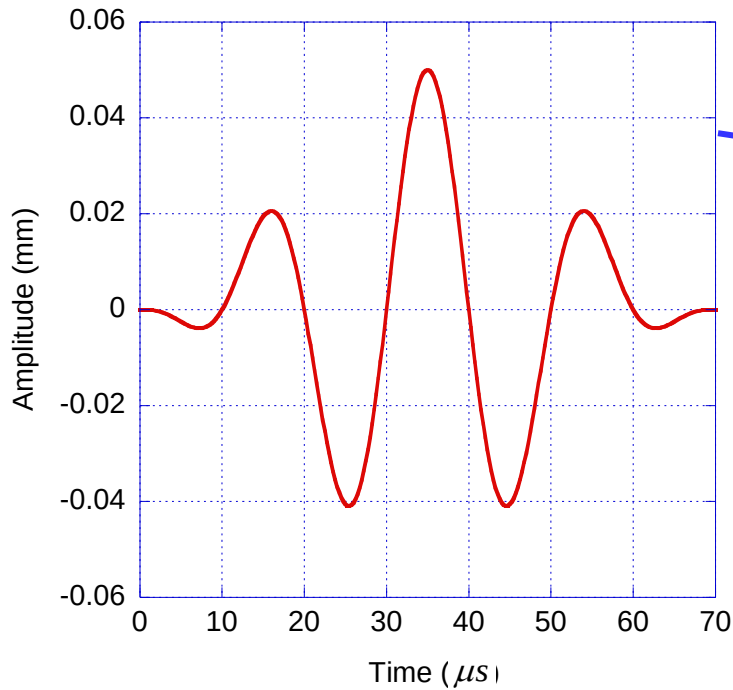
Flange/skin debond



Unit: mm

Sensor nodes	X (mm)	Y (mm)	Z (mm)
10	150.63	3	163.64
11	150.63	3	175.76
12	150.63	3	187.88
13	150.63	3	200.00
14	150.63	3	212.12
15	150.63	3	224.24

Tone Burst Applied to All Actuator Nodes Simultaneously

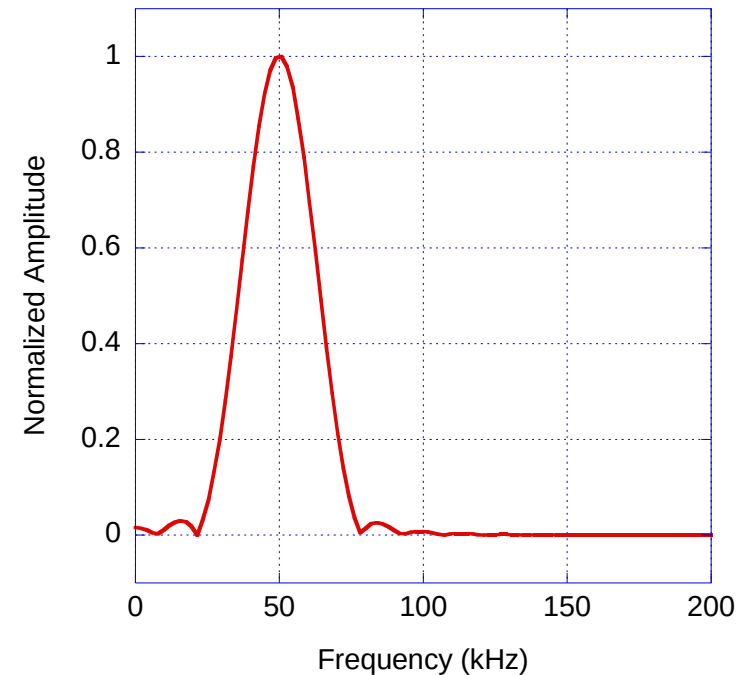


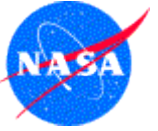
Actuator model
(12 nodes)

Out-of-plane Displacement:

$$U_2(t) = -\frac{A}{2} \sin(2\pi f_c t) \left(1 - \cos\left(\frac{2\pi f_c t}{3.5}\right)\right), \quad \text{for } 0 \leq t \leq 70 \mu s$$

$$0, \quad \text{for } t > 70 \mu s$$

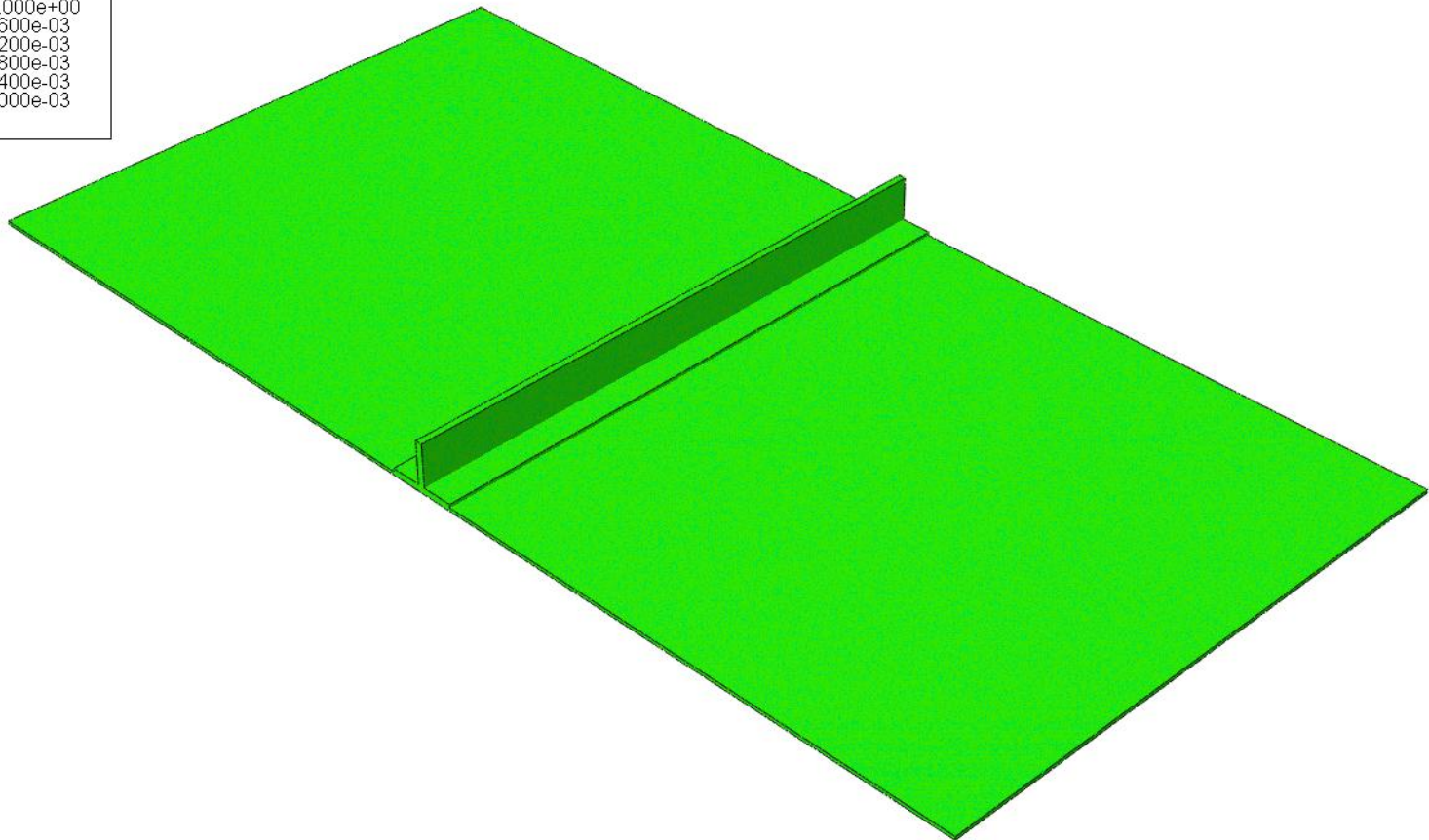
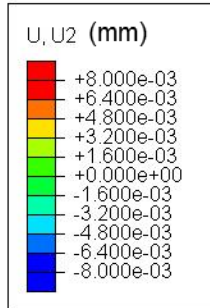
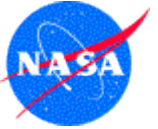


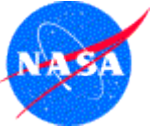


Outline

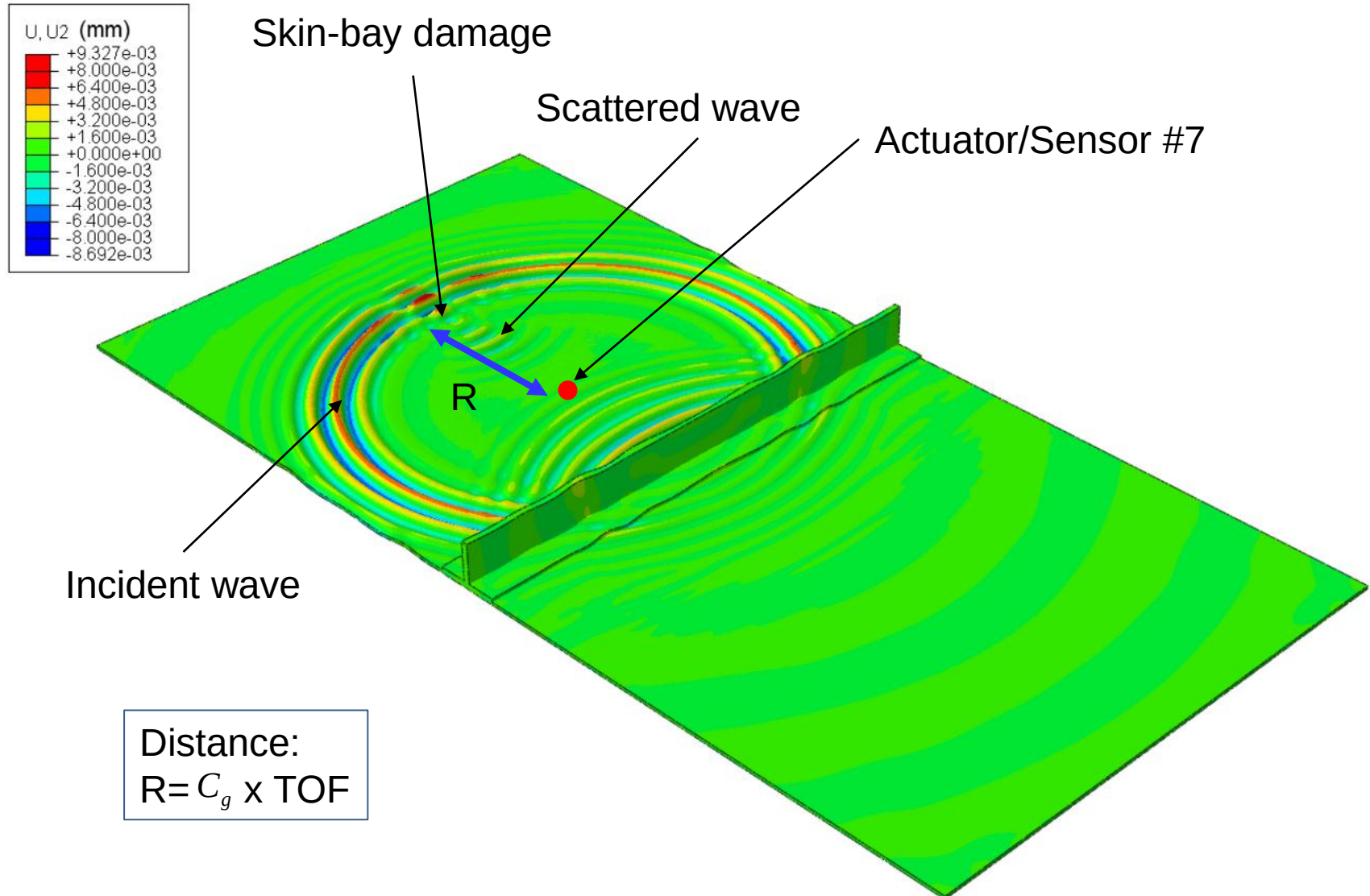
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Flexure Lamb Wave Propagation in Skin-bay Damaged Panel (Movie)

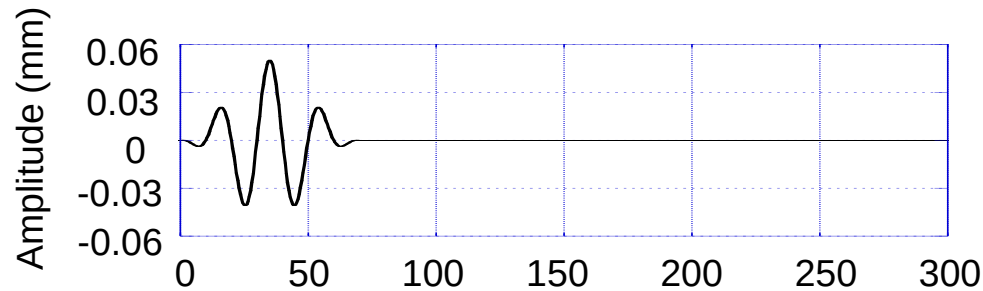
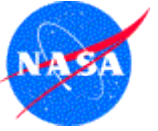




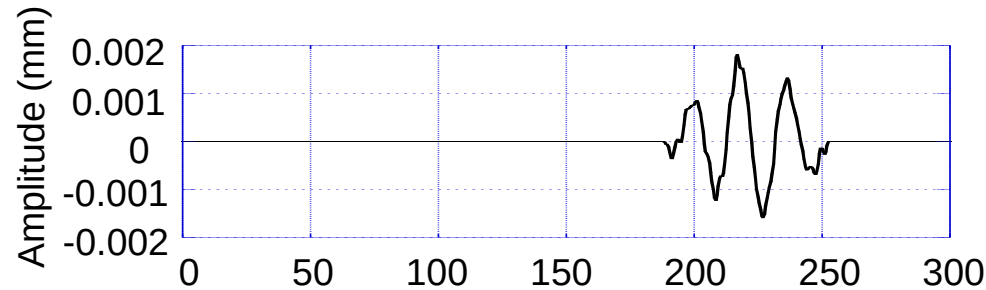
Distance from Actuator to Damage



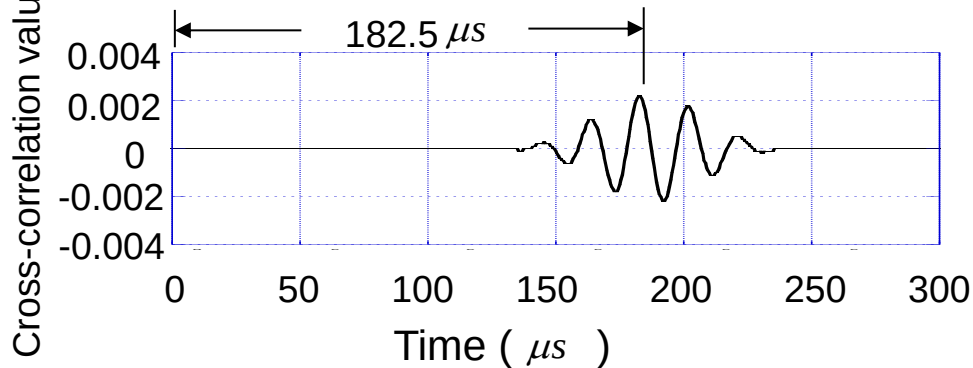
Time Lag for Estimating Time of Flight (TOF)



Tone burst
applied to all
actuator nodes
simultaneously

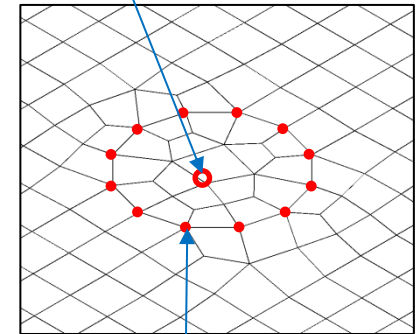


Scattered wave
signal received at
sensor node #7



Time lag determined by the
cross-correlation of the
above two signals

Sensor node (#7)





Time Reversed Scattered Wave Signals to be Reemitted from Sensor Nodes

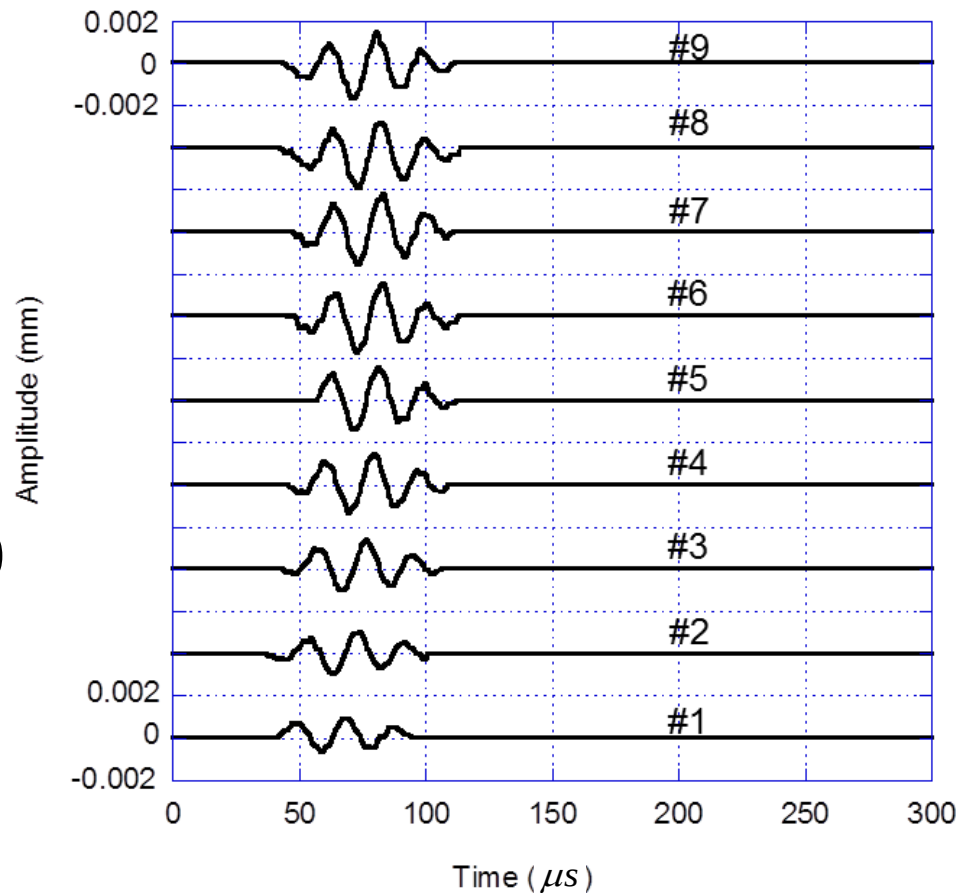
- Scattered Wave Signals:

$$w_{\text{scattered wave}}(t) = w_{\text{damaged panel}}(t) - w_{\text{pristine panel}}(t)$$

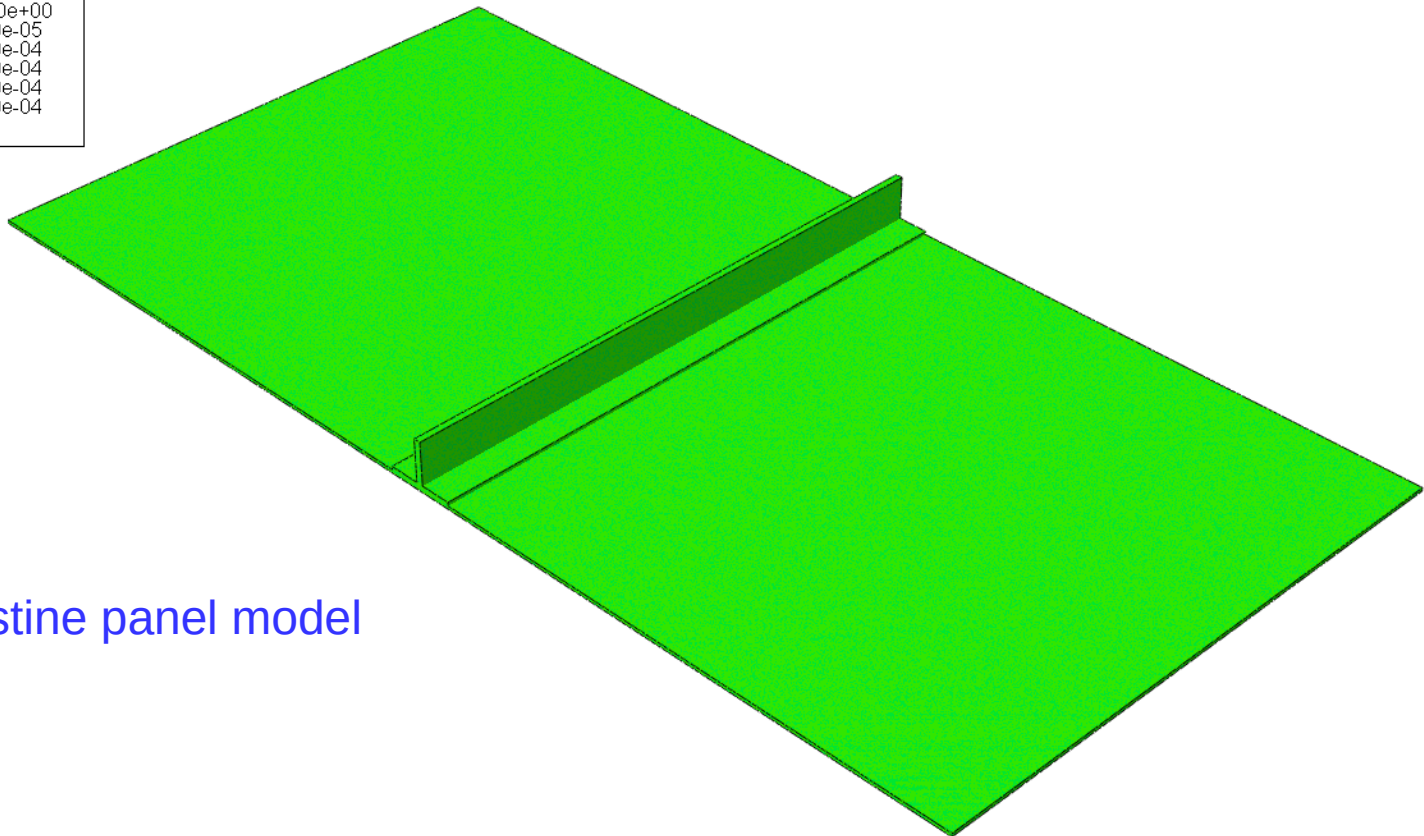
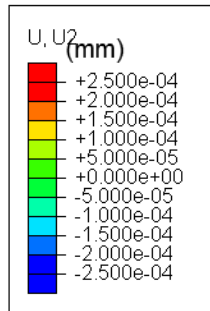
- Time Reversed Signals:

$$w_{\text{scattered wave}}^{TR}(t) = w_{\text{scattered wave}}(T - t)$$

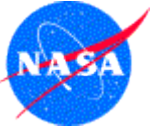
where T is the total time



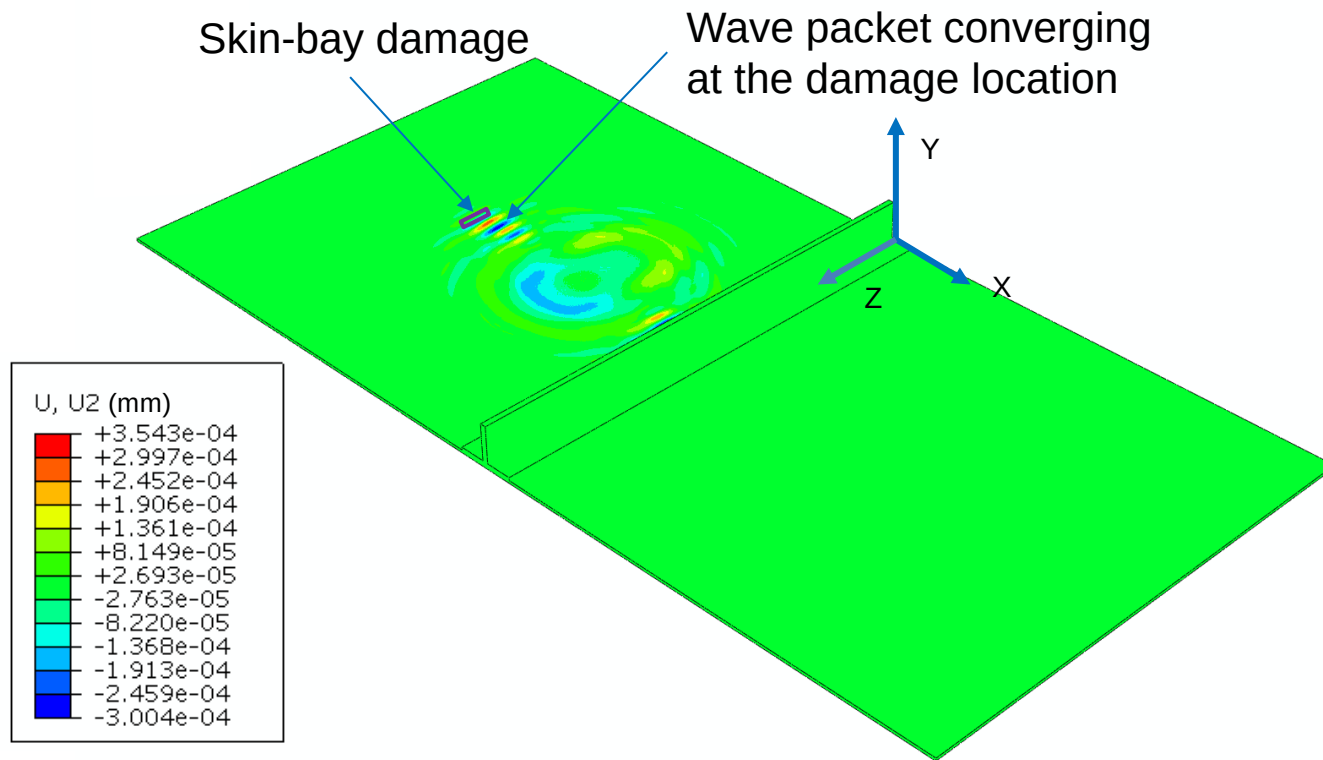
Time Reversal Waves for Skin-Bay Damage Detection (Movie)



Pristine panel model

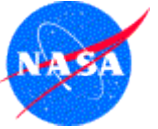


Time Reversal Waves for Skin-Bay Damage Detection



Wave field at $t=152 \mu s$

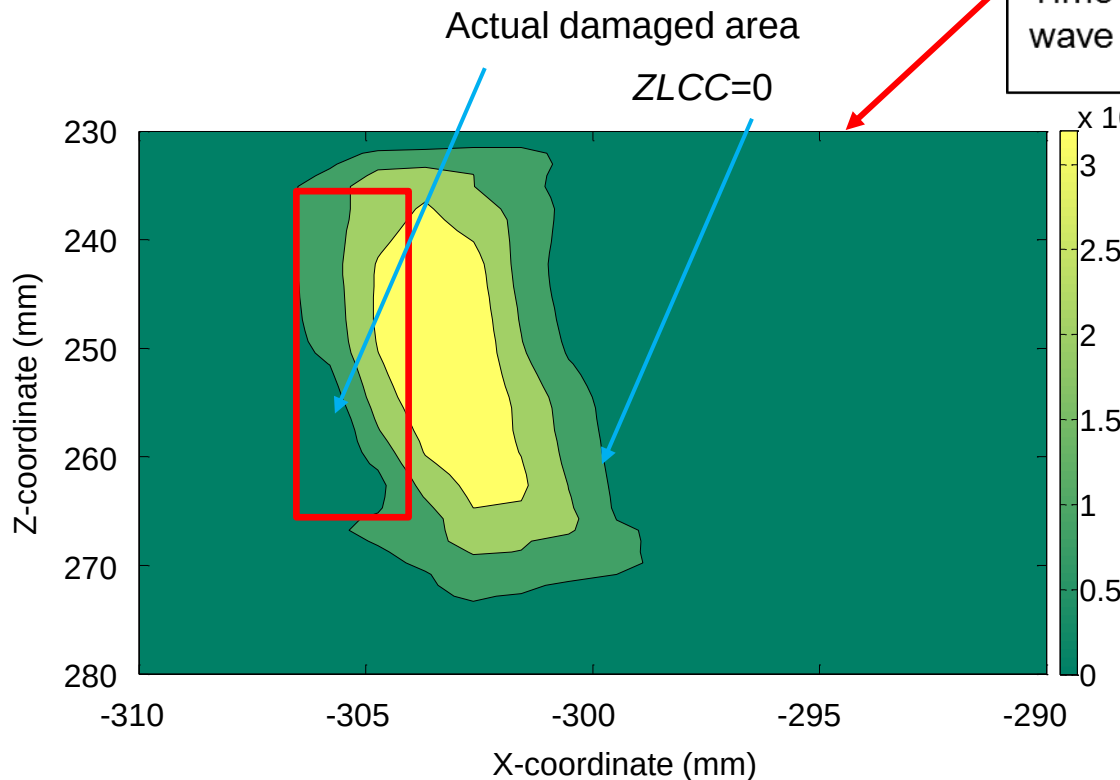
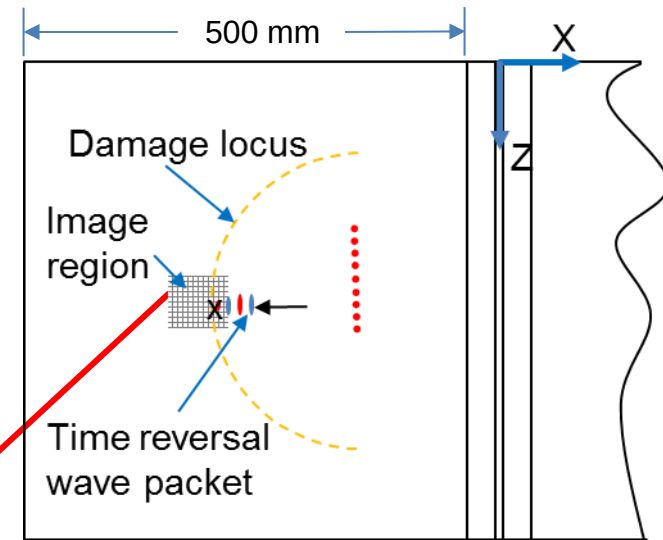
Efficient Damage Imaging Technique



- Image condition is the zero-lag cross-correlation (ZLCC) which computed at node (i) as :

$$ZLCC(i) = \sum_{n=0}^{N-1} w_{incident\ wave}^{TR}(n) \times w_{time\ reversal\ wave}(n)$$

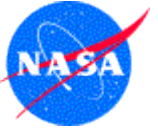
- ZLCC values computed at nodes neighboring to location X to minimize the image region area



Damage image
very close to
actual damage

Refs:

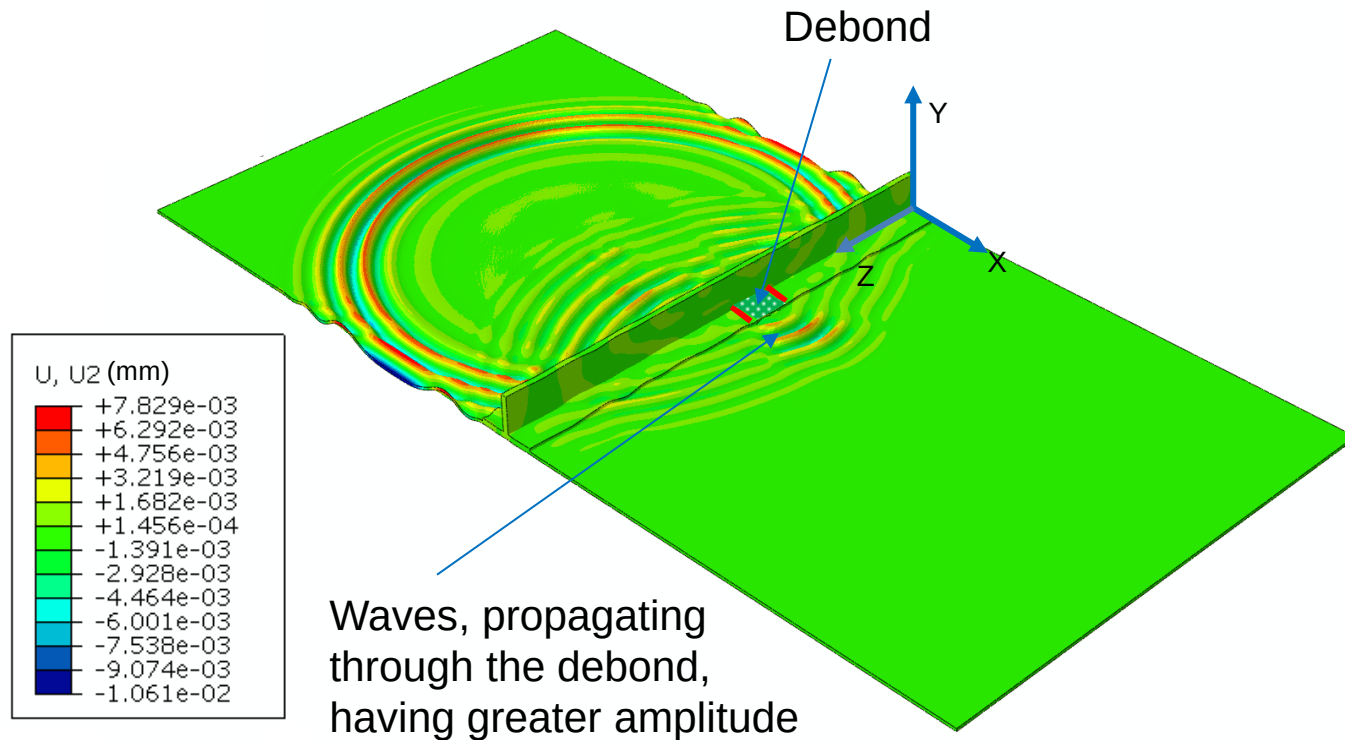
1. Berkhout, Imaging of acoustic energy by wave field extrapolation, 1982
2. Claerbout, Imaging the earth's interior, 1985



Outline

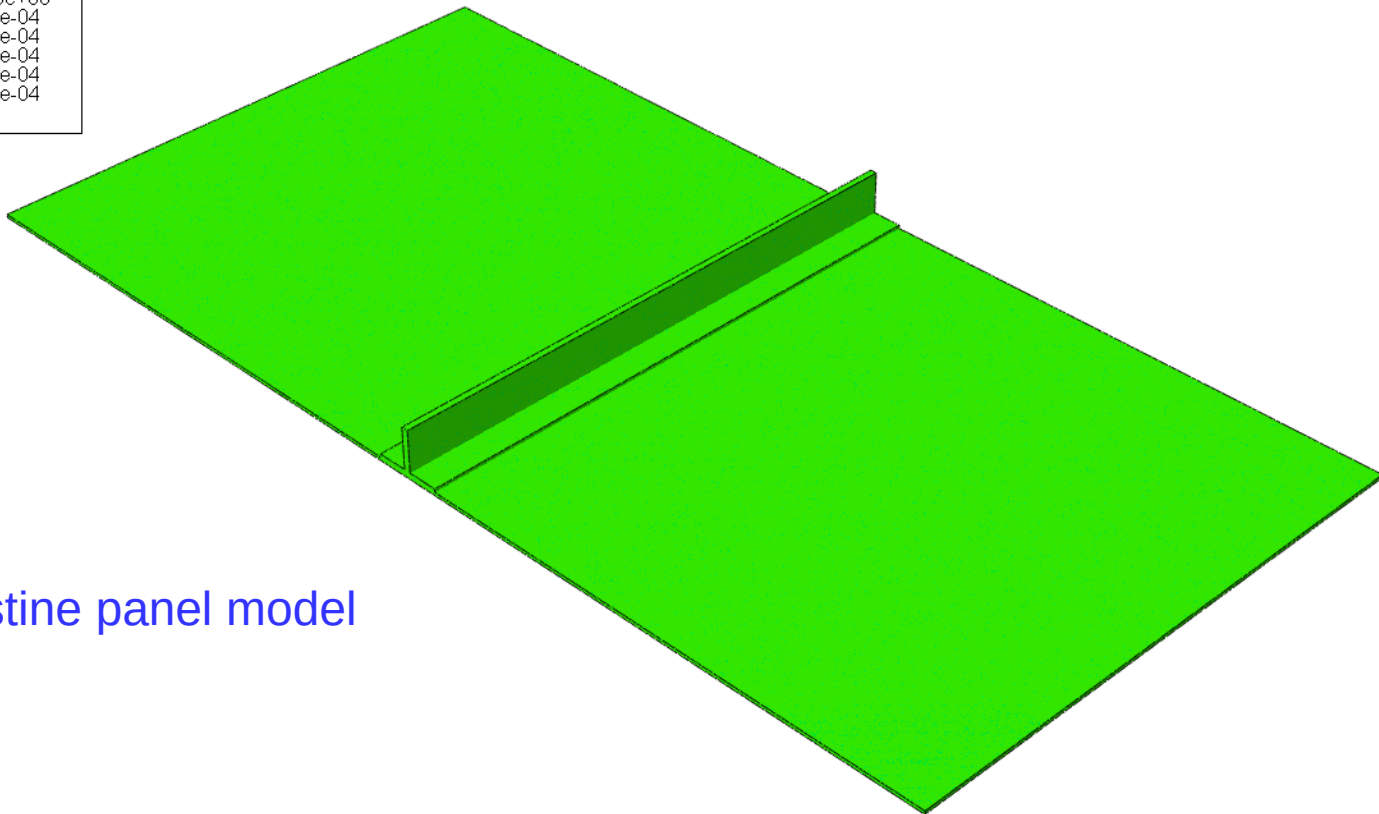
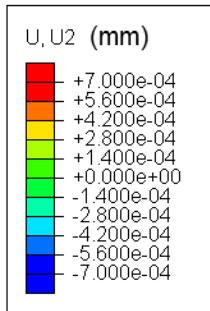
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Snapshot of Propagating Flexural Wave in the Debond Panel



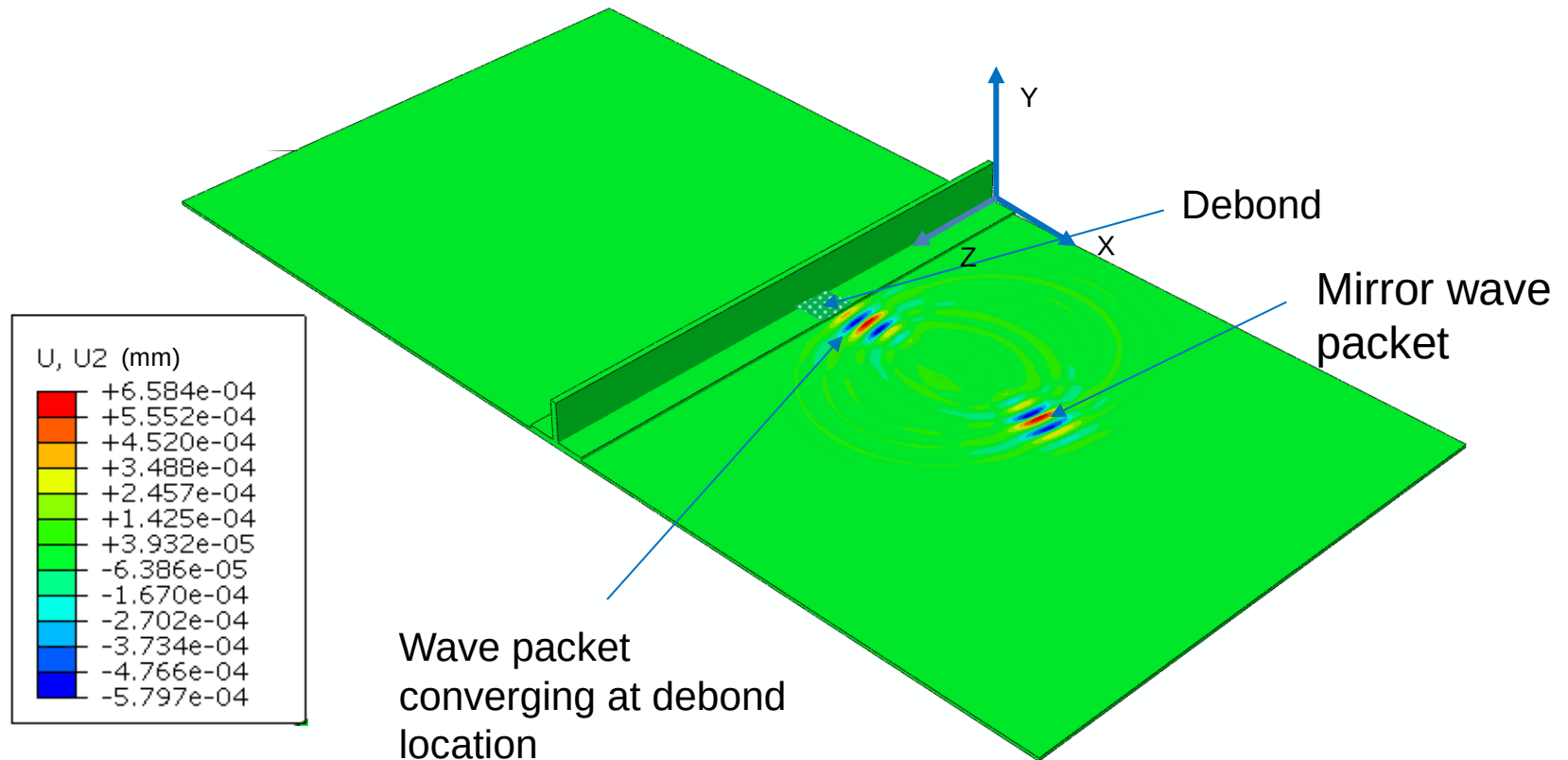
Wave field at $t = 175 \mu s$

Time Reversal Waves for Debond Detection (Movie)



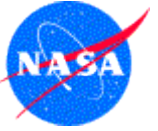
Pristine panel model

Time Reversal Waves for Debond Detection



Time reversal wave field at $t=140 \mu s$

- Debond size investigation yet to be completed
- TOF information used to determine if the mirror wave packet caused by another damage



Concluding Remarks

- Commercial finite element code can be conveniently used for simulating Lamb wave damage detections for stiffened composite panels
- An efficient damage imaging technique was found to have potential for accurate damage detection for the skin-bay damaged panel
- More systematic investigation of the actuator and sensor placements is needed to improve the accuracy of the damage size identification
- More advanced methods are needed for detecting multiple damages/damage modes in composite aircraft structures