Modeling and Simulation for Enabling In-space NDE and Health Monitoring

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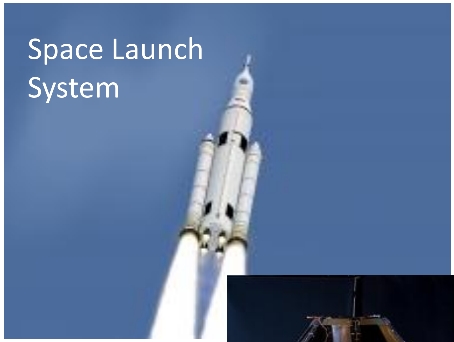
NASA In-Space Inspection Workshop
July 15-16 2014, Houston, TX

Outline

- In-space inspection - goals, needs
- Simulation tools in NDE and SHM
    - Special Needs for In-space Applications
    - NESB Examples
    - State-of-art in the field
- On-going NESB research
- Future Direction and Needs

In-space Inspection

- Goal: Ensure safety, durability, reliability and mission success
- Needs:
  - Inspection techniques for advanced materials/designs: *must have* methods to establish confidence in inspection capabilities
  - In-situ monitoring: *must have* validation methods for in-situ autonomous health monitoring
- Enables:
  - Triggered inspection
  - Rapid damage location and assessment
  - Informed decisions (repair/mission change)
- These capabilities enable optimized next generation designs due to confidence in monitoring/detection



Orion Crew Module

Composite hydrogen fuel tank

General: NDE and SHM Simulation

- Realistic NDE simulation tools enables inspection prediction
  - Establish confidence in ability to inspect complex composite joints, and ‘hard to reach’ locations, to cover large areas, one-off parts
  - Predict inspectability during design stage to avoid ‘un-inspectable’ designs or allow more lead time for developing new NDE approaches
- Aid in understanding inspection data
- Creates cost-effective tools for developing and optimizing *damage characterization* techniques
- Simulations enable cost-effective in-situ autonomous monitoring system validation/POD (and are likely required in terms of feasibility)
  - Health monitoring systems are needed to: trigger inspection, reduce the time to locate critical damage, enable informed decision making for repair options

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1. MODELS MUST BE APPROPRIATE FOR THE APPLICATION
2. SIMULATIONS MUST BE VALIDATED

In-Space: Special Considerations

- Ground based modeling for on-orbit:
  - Simulation: NDE/SHM consideration at design state (more lead time), inspection prediction, ground based support for data interpretation, support for inspection method selection
- On-orbit computation and models:
  - As computational power increases, on-orbit modeling enabled
  - On-orbit solutions to unexpected scenarios (~4-22 minutes for 1-way communication to Mars; also can have planetary alignment issues)
- On-orbit computations must either
  - Have low computational demand to run on traditional resources (laptop)
  - Or, use latest low-weight HPC technology such as GPU, Phi (i.e. clusters in space not realistic route)

Trend: Computational Resources

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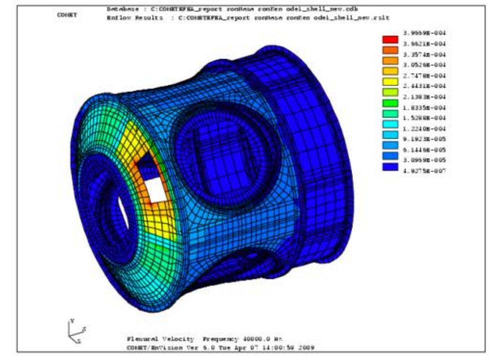
- Computational power per unit space increasing, cost decreasing
- iPad2 has as much processing power as Cray 2 (world's fastest computer in mid 1980s)
- A job that took 24 hours in 1996 – less than second today
- Fastest computer:
  - 1996: 220 giga flops (10^9)
  - 2013: 33 peta flops (10^{15})
- Cost per GFLOP (adj for inflation)
  - 1984: $42M
  - 1997: $42k
  - 2007: $52
  - 2013: $0.12

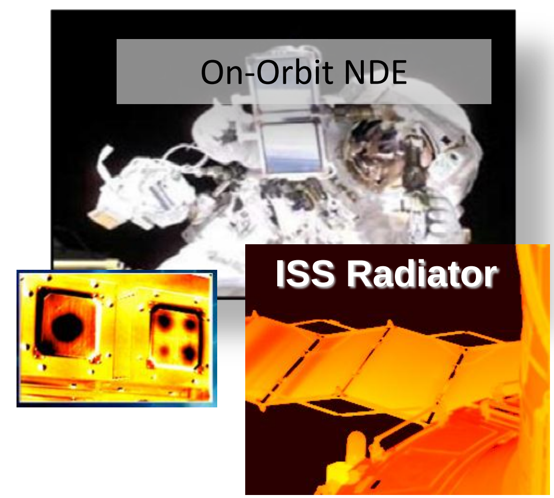
Cray 2 Supercomputer
NASA Langley Research Center 3/23/1989 Image # EL-2001-00428

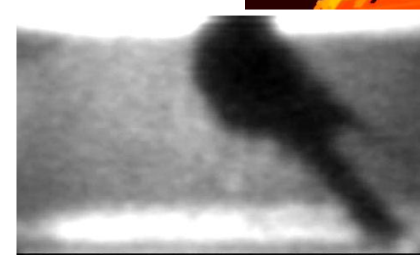
http://www.tuaw.com/2011/05/09/ipad-2-would-have-bested-1990s-era-supercomputers/

NESB Examples



- ISS Leak Location: (Presentation by Eric Madaras, Session 4)
  - Utilizes ground-based simulations of sound dissipation in the ISS modules for data analysis
- EVA IR Camera:
  - Thermal models implemented to determine applicability to in-space setting (heat dissipation in 2.7 Kelvin)
- X-ray Backscatter:
  - Model aids in data analysis, compare received signal to modeled signal

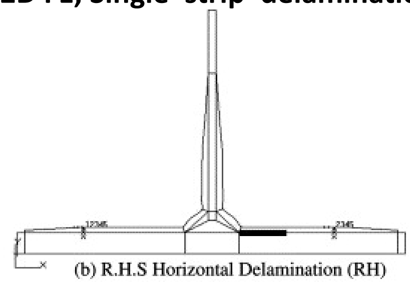




SOA and Gaps

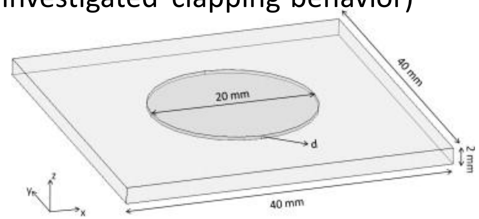
- SOA of NDE and SHM modeling/simulation *not adequate* for future needs, including:
  - Larger scale simulations
  - Composites
  - Advanced designs
  - Realistic damage scenarios

2D FE, Single 'strip' delamination



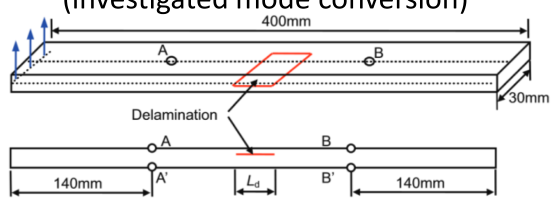
Kesavan, A., et al. "Damage detection in T-joint composite structures." *Composite Structures* 75.1 : 313-320. **(2006)**

3D FE, Single circular delamination
(investigated 'clapping' behavior)



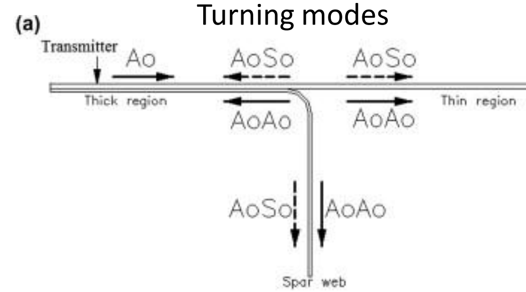
From: Delrue, Steven, and Koen Van Den Abeele. "Three-dimensional finite element simulation of closed delaminations in composite materials." *Ultrasonics* 52, pp 315-324 **(2012)**

3D FE, Single rectangular delamination
(investigated mode conversion)



From: Liu, Zenghua, et al. "Delamination detection in composite beams using pure Lamb mode generated by air-coupled ultrasonic transducer." *Journal of Intelligent Material Systems and Structures*: 1045389X13493339. **(2013)**

2D FE (ANSYS)
Turning modes



Ramadas, C., et al. "Interaction of Lamb mode with structural discontinuity and generation of "Turning modes" in a T-joint." *Ultrasonics* 51.5: 586-595. **(2011)**

Real Composite Damage

X-ray CT of PRSEUS Joint, From NASA TM-2013-217799 by Patrick Johnston

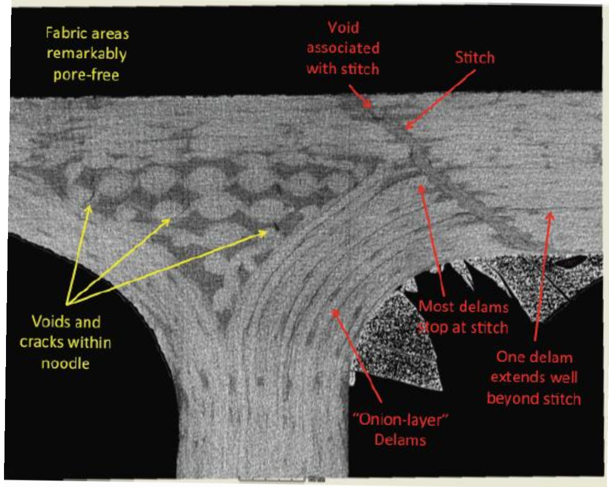


Figure 4.22. X-ray CT slice showing noodle and inner fillet region.

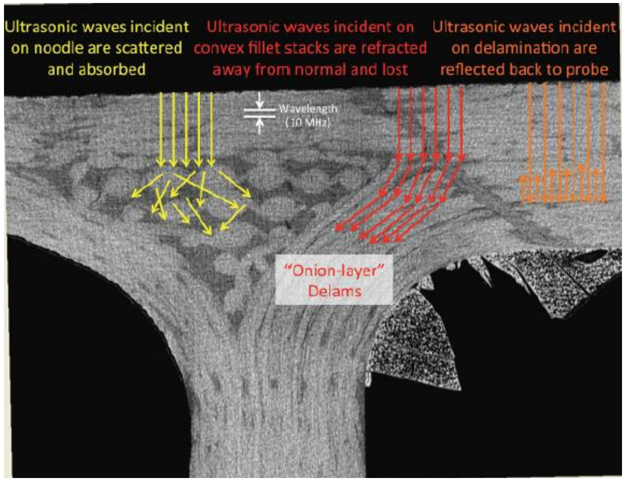
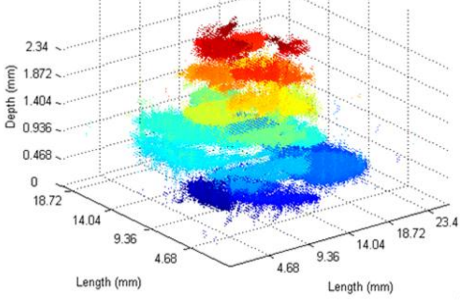
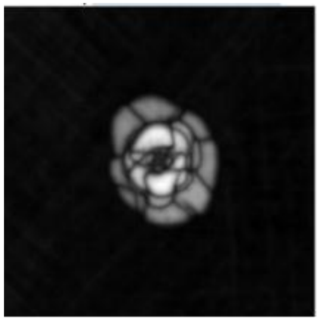


Figure 5.1. X-ray CT slice with superimposed ultrasonic ray tracings to schematically explain the interpretation of ultrasonic data.

X-ray CT data of delamination damage



UT data of delamination damage



X-ray CT data of microcrack damage

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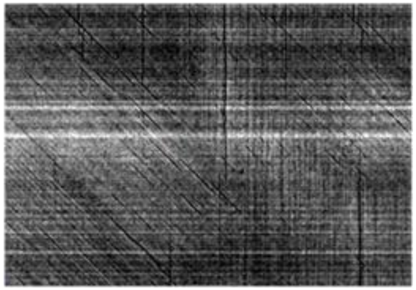


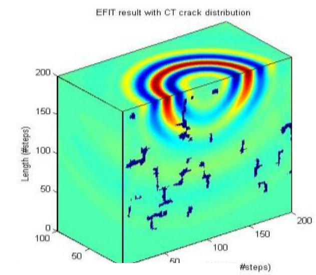
Example of On-going Work: NESB Simulations

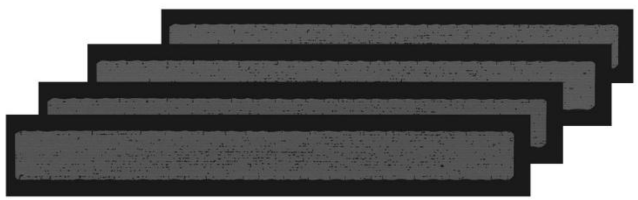
- Custom code can simulate 3D wave interaction with realistic damage

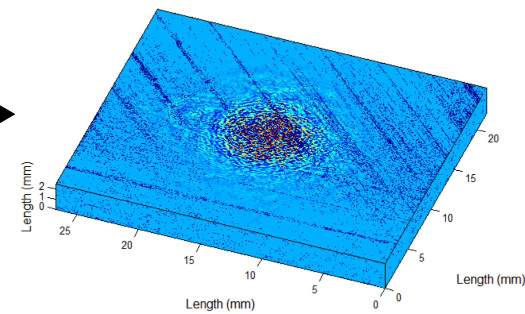
µCT Slice

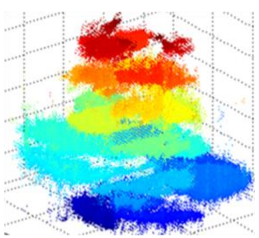
CT crack image created by Ray Parker, NESB

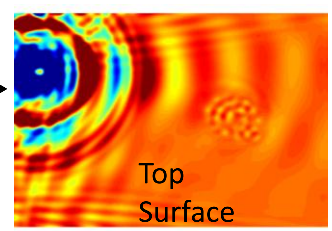
Read CT crack data into Simulation

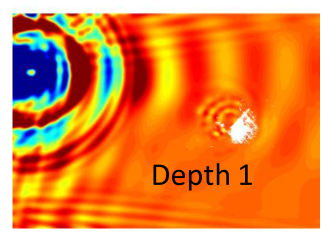


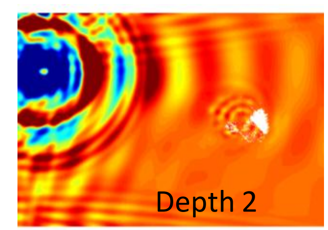










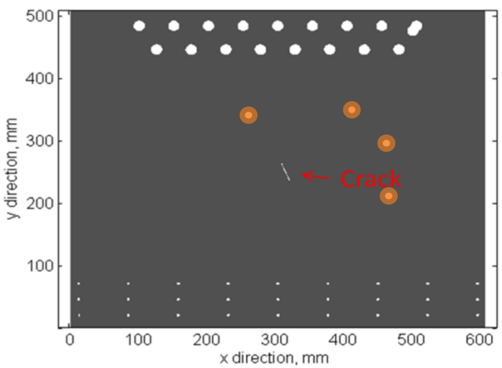


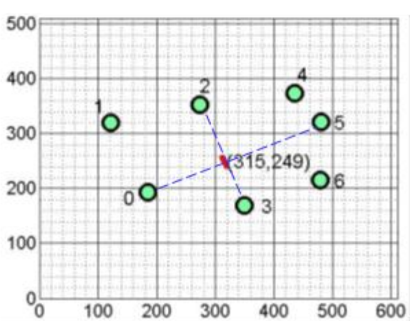
Leckey, Cara AC, Rogge, Matthew and Parker, F. Raymond. "Guided waves in anisotropic and quasi-isotropic aerospace composites: Three-dimensional simulation and experiment." *Ultrasonics* 54.1 (2014): 385-394.

Health Monitoring Example: NASA/Univ. South Carolina

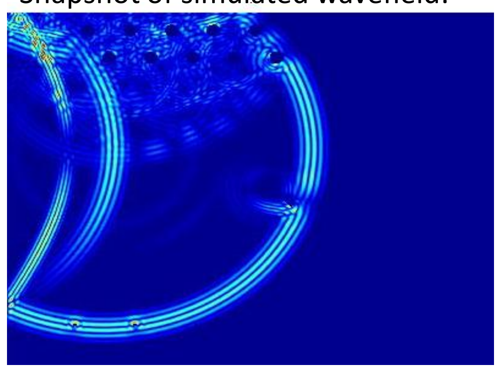

Piezo wafers
Image from www.steminc.com

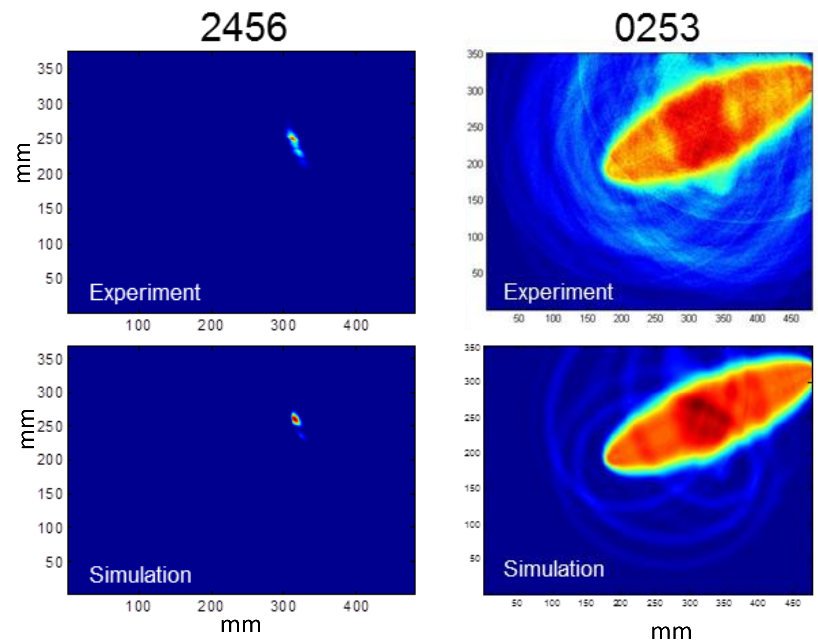
- Sparse arrays = requires fewer sensors, lower cost, less added weight
- Simulations provide potential method to validate SHM system coverage, limitations, and detectability
- **Results demonstrated use of 3D simulation data in place of experimental data for investigating sensor location w.r.t. damage**
- **Certain sensor locations led to very poor damage detection/characterization**





Snapshot of simulated wavefield:



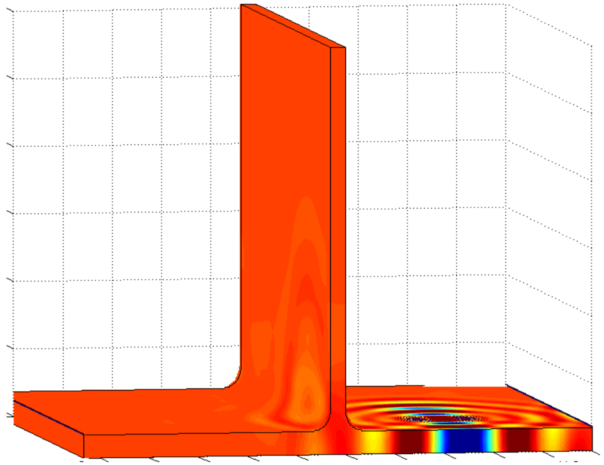


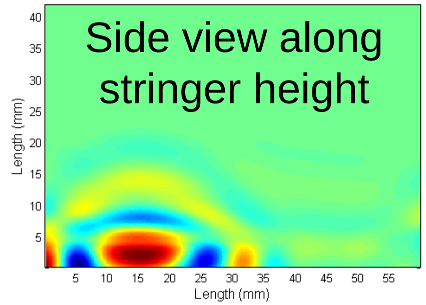
Work performed under SAA 11-81

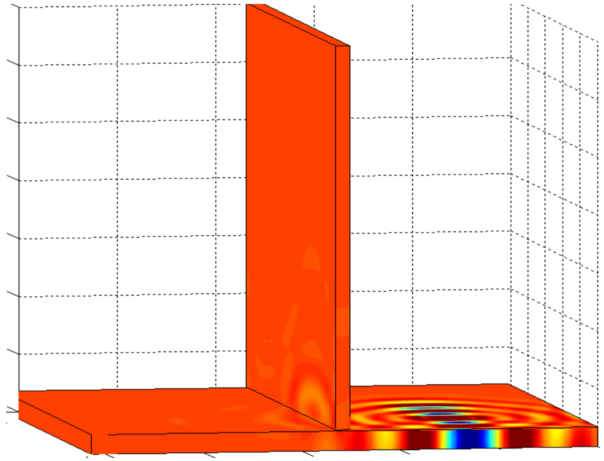
[1]Yu, L. and Leckey, C. "Lamb Wave Based Quantitative Crack Detection using a Focusing Array Algorithm". *Journal of Intelligent Material Systems and Structures*, Vol 24, pp 1138-1152 (2013)

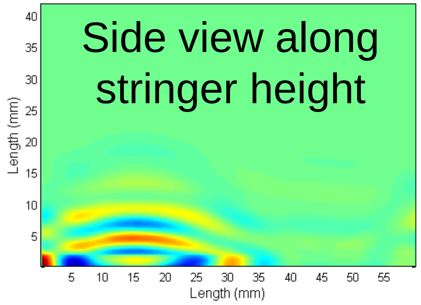
Larger Scale Complex Components

- Need to push towards larger scale structural components
  - T-stiffener, unidirectional composite IM7/8552, 70 mm x 70 mm x 42 mm









Future Direction/Needs

- Realistic NDE and SHM simulations are needed that leverage emerging computing technologies
  - MIC (Intel Xeon Phi), GPU
- Simulation tools **MUST** be validated to be useful
- Interest in demonstrations of how modeling/simulation can enhance inspection capabilities via:
  - Optimized damage characterization/detection
  - Improved analysis and data interpretation
  - Improved confidence in inspectability
  - Use of simulations for validating capabilities and limitations of health monitoring systems
  - Show how realistic simulations can play a role at the design stage

Thanks to:
Dr. Bill Winfree, NASA LaRC
Prof. Linyu Yu, University of South Carolina
F. Raymond Parker, NASA LaRC

Questions?