quartus

ENGINEERING FORWARD

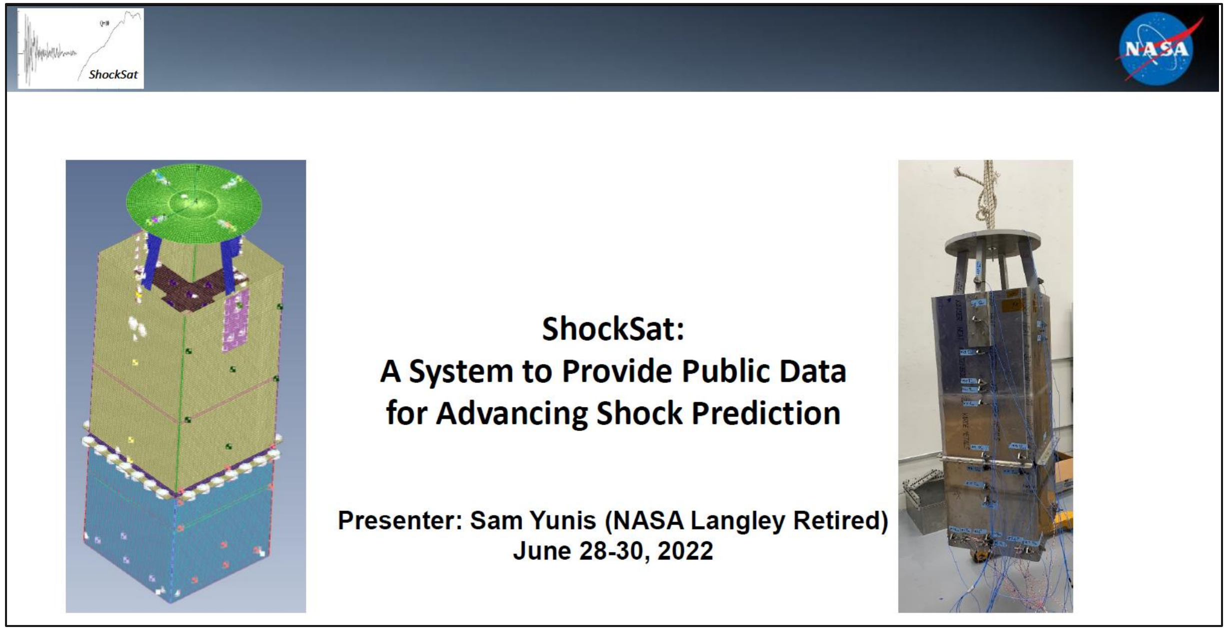
INSIGHTS INTO THE SHOCK RESPONSE OF THE NASA SHOCKSAT FROM EXPLICIT DYNAMICS FEA

Spacecraft and Launch Vehicle Dynamic Environments Workshop
June 5, 2024

JOSHUA E. GORFAIN

Motivation

- Shock is a persistent challenge – is discussed at this forum every year
- Primary Question: How well does Explicit Dynamics FEA perform for a spacecraft-like structure?
- NASA ShockSat used here as an open-source case study, *focusing on impact hammer tests*



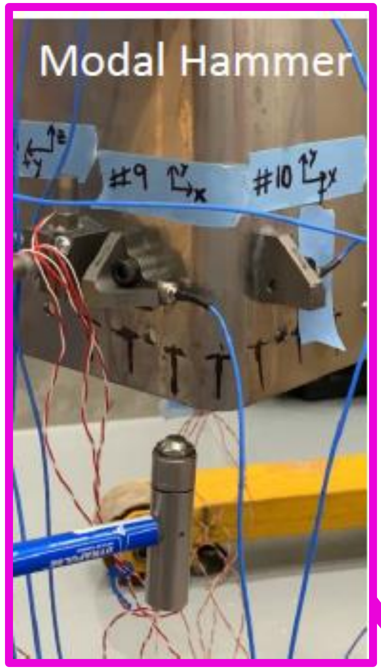
quartus

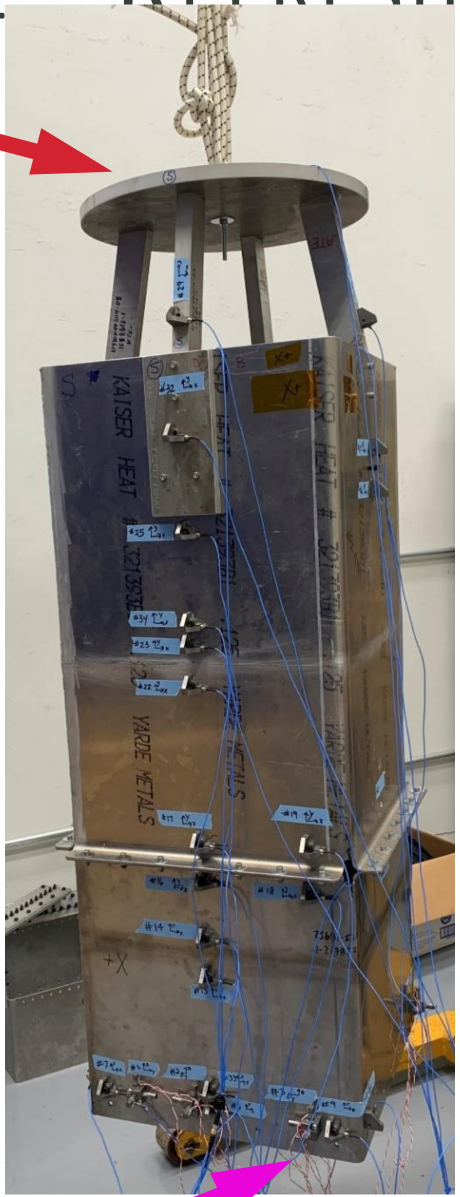
Overview

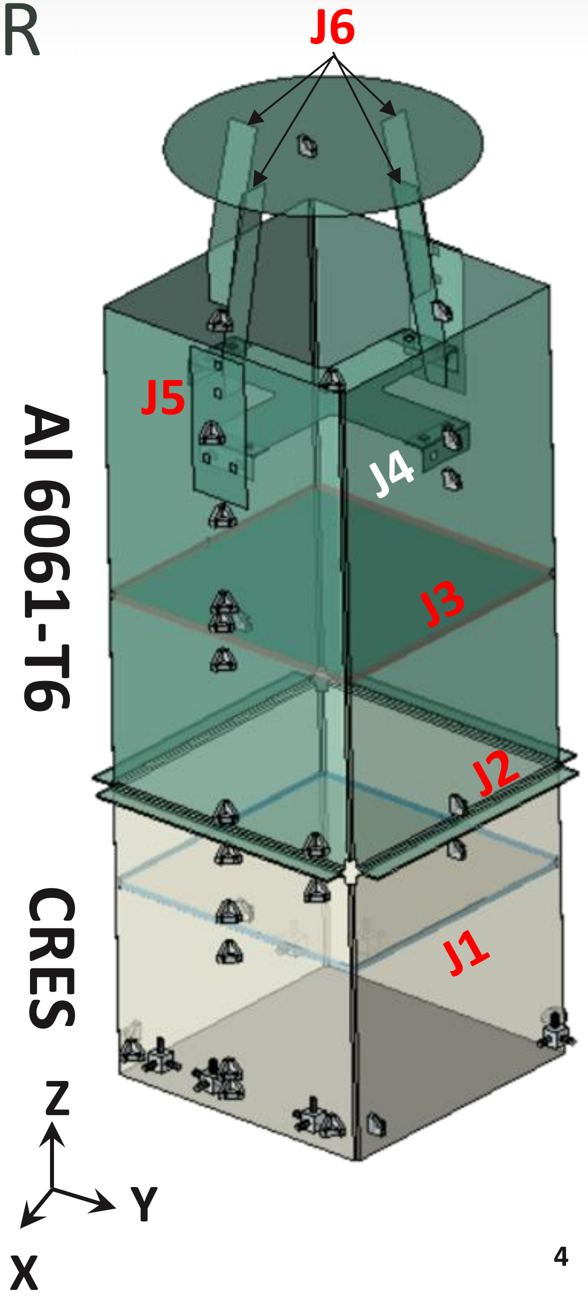
- NASA ShockSat Background
- Analysis Approach & Model
- Physical Insights from Test and Analysis
- Conclusions

NASA ShockSat Test Article - Refresher

- Metallic structure suspended from top
  - 1.5’ sq x 5’H, ~200 lbs
  - Mostly 0.125” plate
  - Thick strut, dish & doublers
- Various types of joints (J#)
- 36 shock triax accelerometers
- Impact hammer strikes are point shock source
  - Axial (+Z)
  - Normal (-X)







quartus

Approach – Explicit Dynamics FEA

What it is:

- Fully-nonlinear, transient finite element analysis method
  - Direct time integration, solves conservation equations
- Specifically designed for stress-wave propagation = fundamental physics of shock transmission
  - No limitations on nonlinearities or time scales (frequency bandwidth)

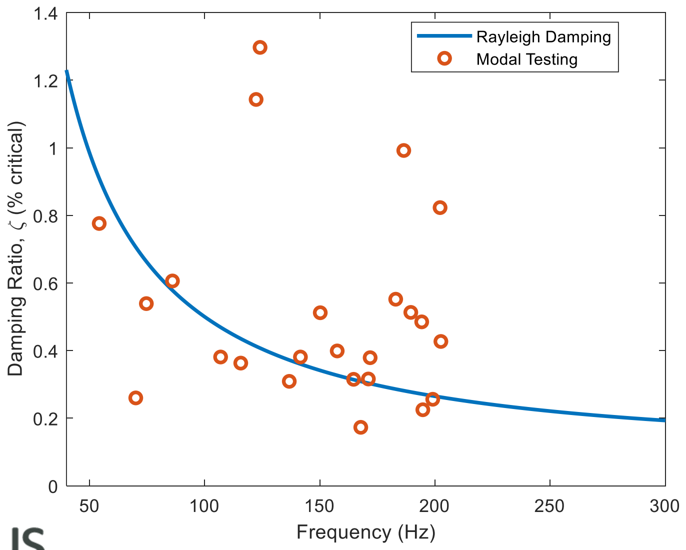
Application here:

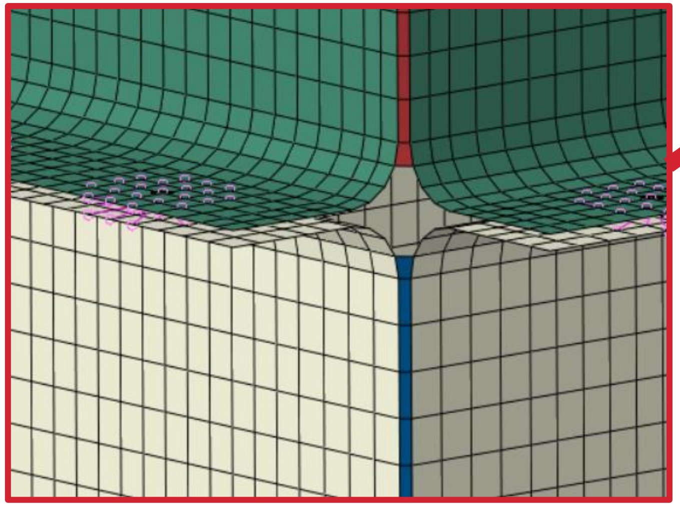
- Translate NASA-provided NASTRAN FEM into Abaqus\Explicit, ***with minimal modification***
- Directly apply measured impact force, compute event out to 100 ms
- Signal process data from simulation & experiment ***identically***
- In-depth comparison of measurements and predictions ***without subsequent tuning***

quartus

MODEL OVERVIEW

- NASA-provided, modal-correlated to < 200 Hz
  - Shell elements ~0.25” sized → ~7 elems./wavelength at 10 kHz
- Kept linearized joint treatments (e.g. rigid patches with zero-length springs)
  - *No contact or high-fidelity fastener modeling used, though easily could have*
- *Only modifications made here:*
  - Replaced point mass-rigid accelerometers with explicit models
  - Added simple estimate of Rayleigh damping from modal test data

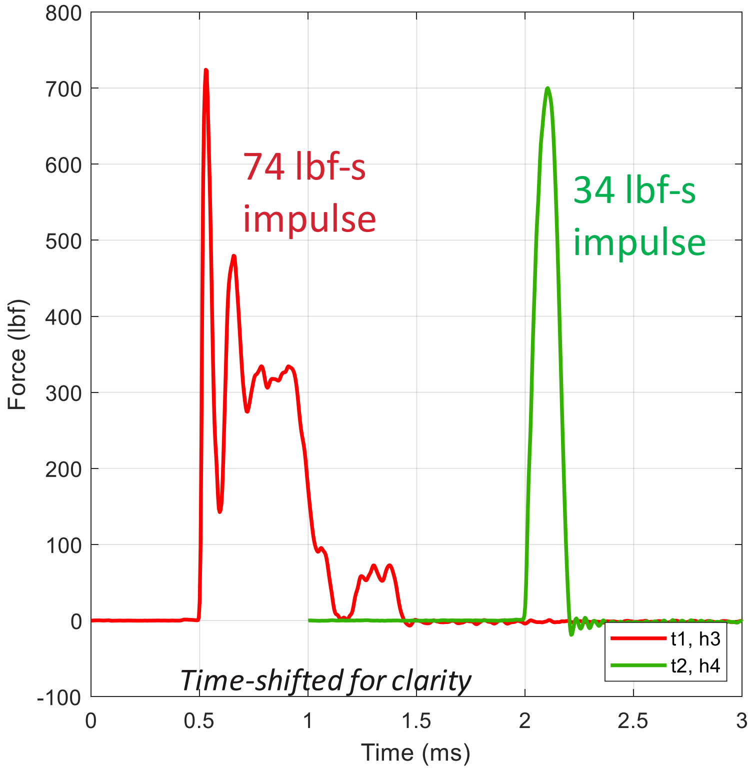


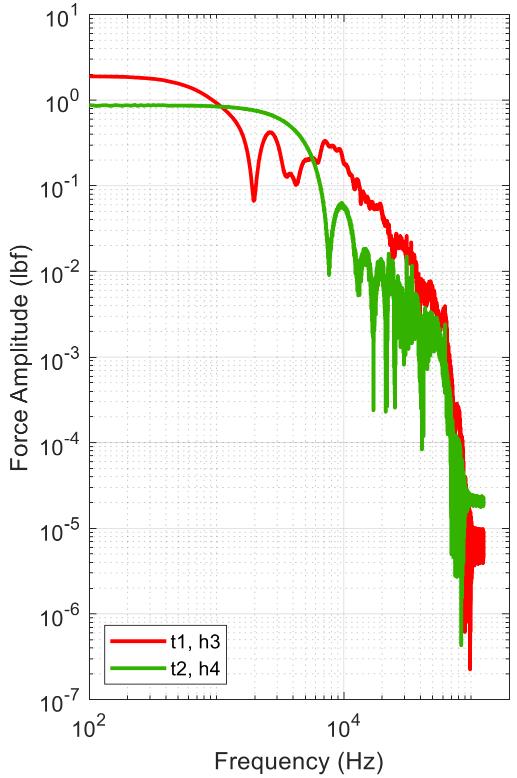


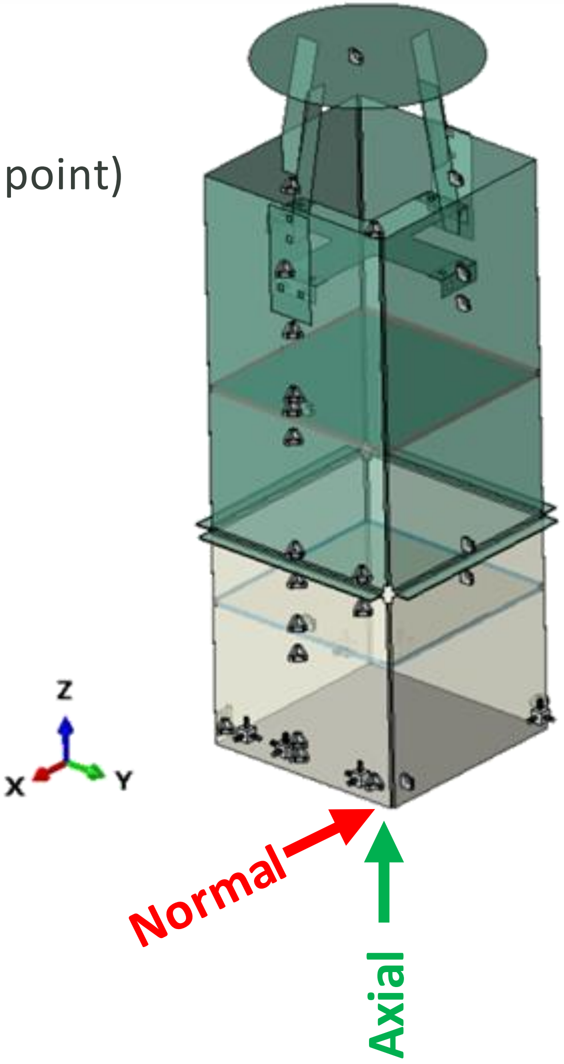
quartus

Model Excitation - Hammer Impacts

- Selected nominal hits among replicates for *two different impact orientations*
  - There was some variability in forcing function, especially for normal hits (soft strike point)
  - Significant lack of energy above characteristic pulse frequencies (2 & 4 kHz)







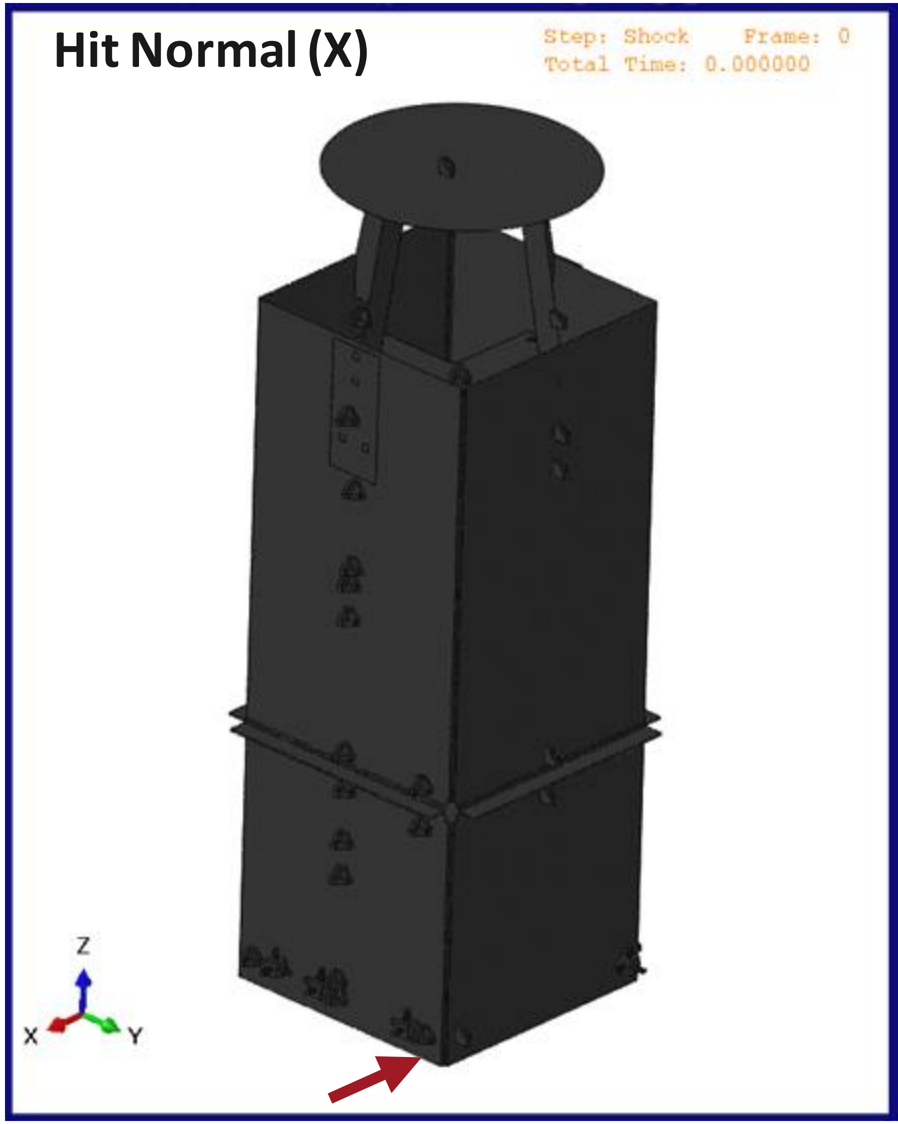
Same force levels - but different: impulse, waveforms & direction

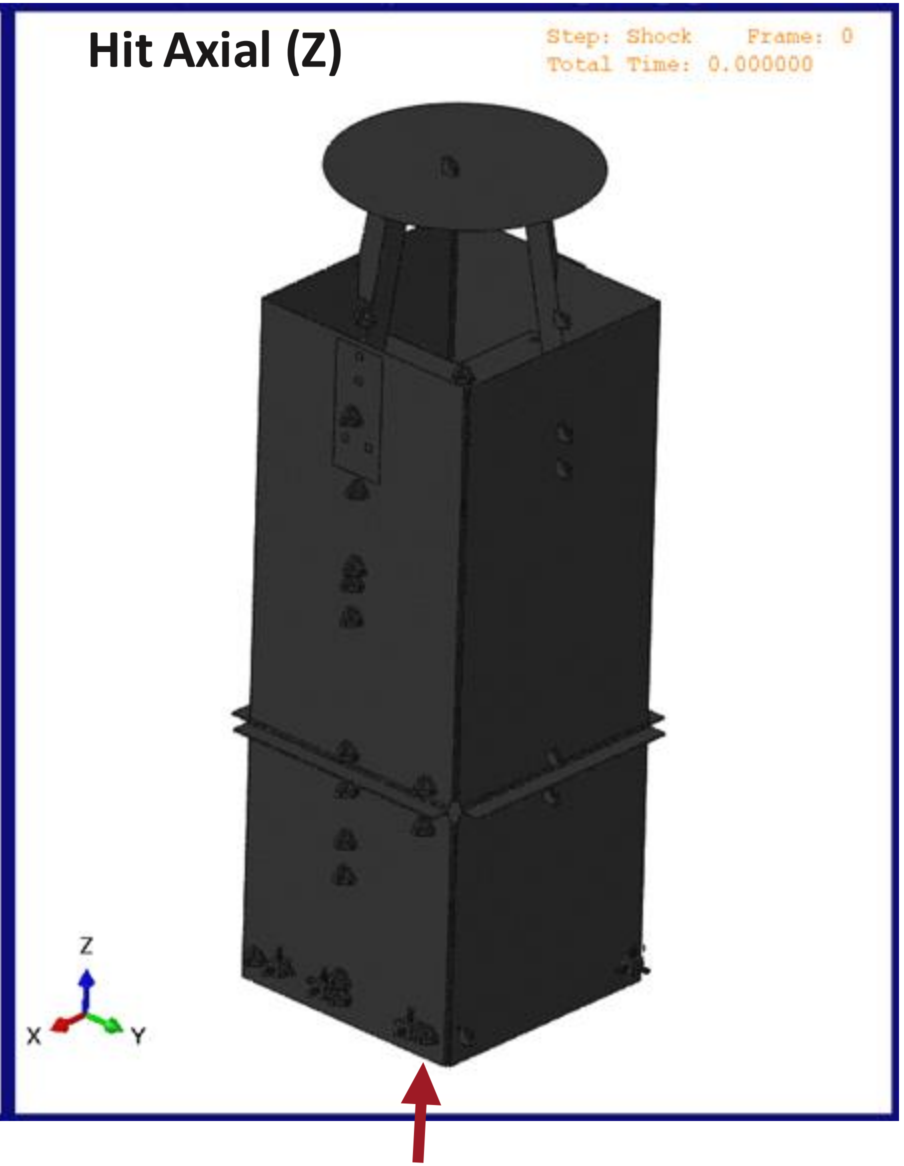
quartus

STRESS WAVE PROPAGATION

- Animations shown in slow-motion until 2 ms
- Effect of impact orientation seen
  - Shock energy input delivered

Distinct wave propagation sensitivity to impact orientation

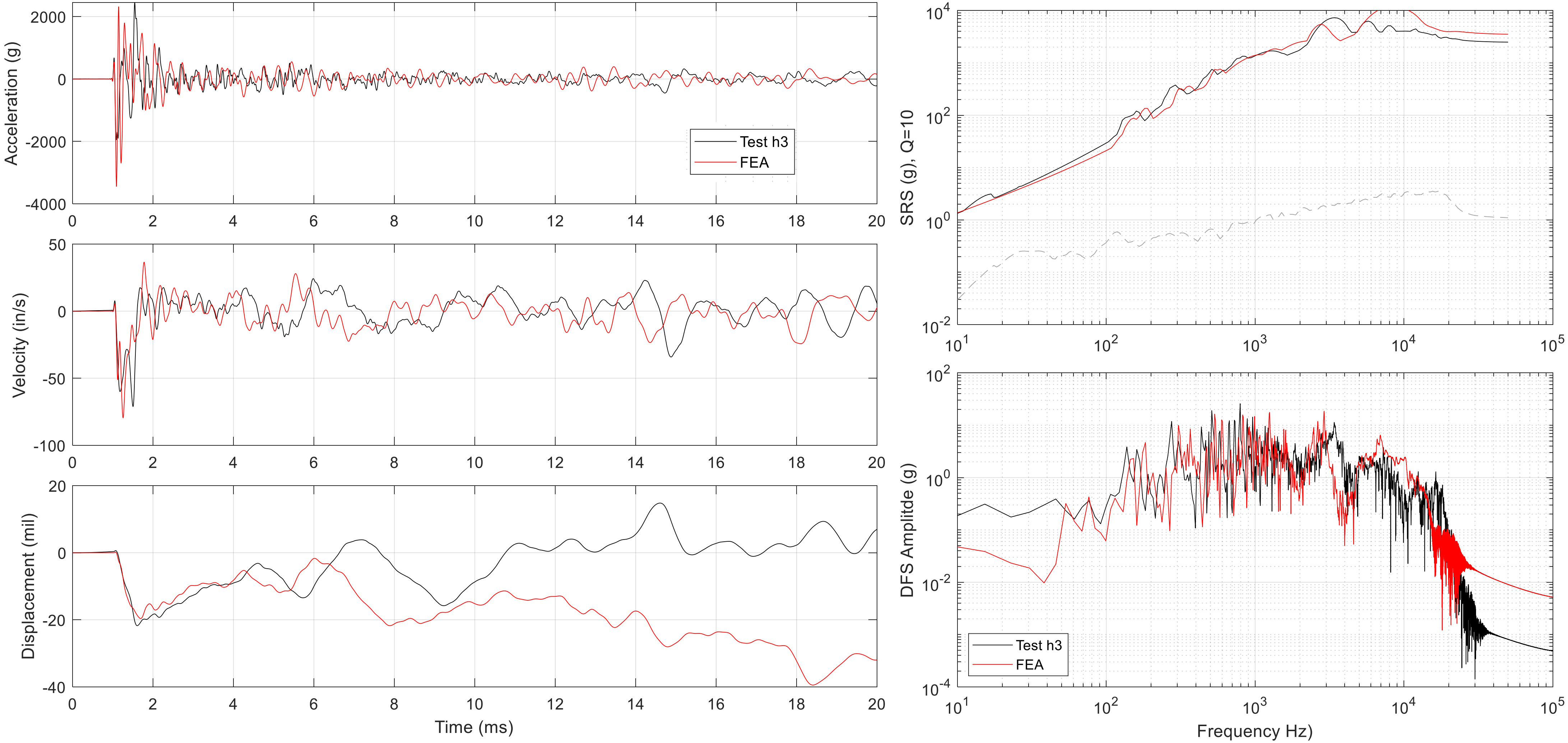




quartus

Sample Response: Normal At Source

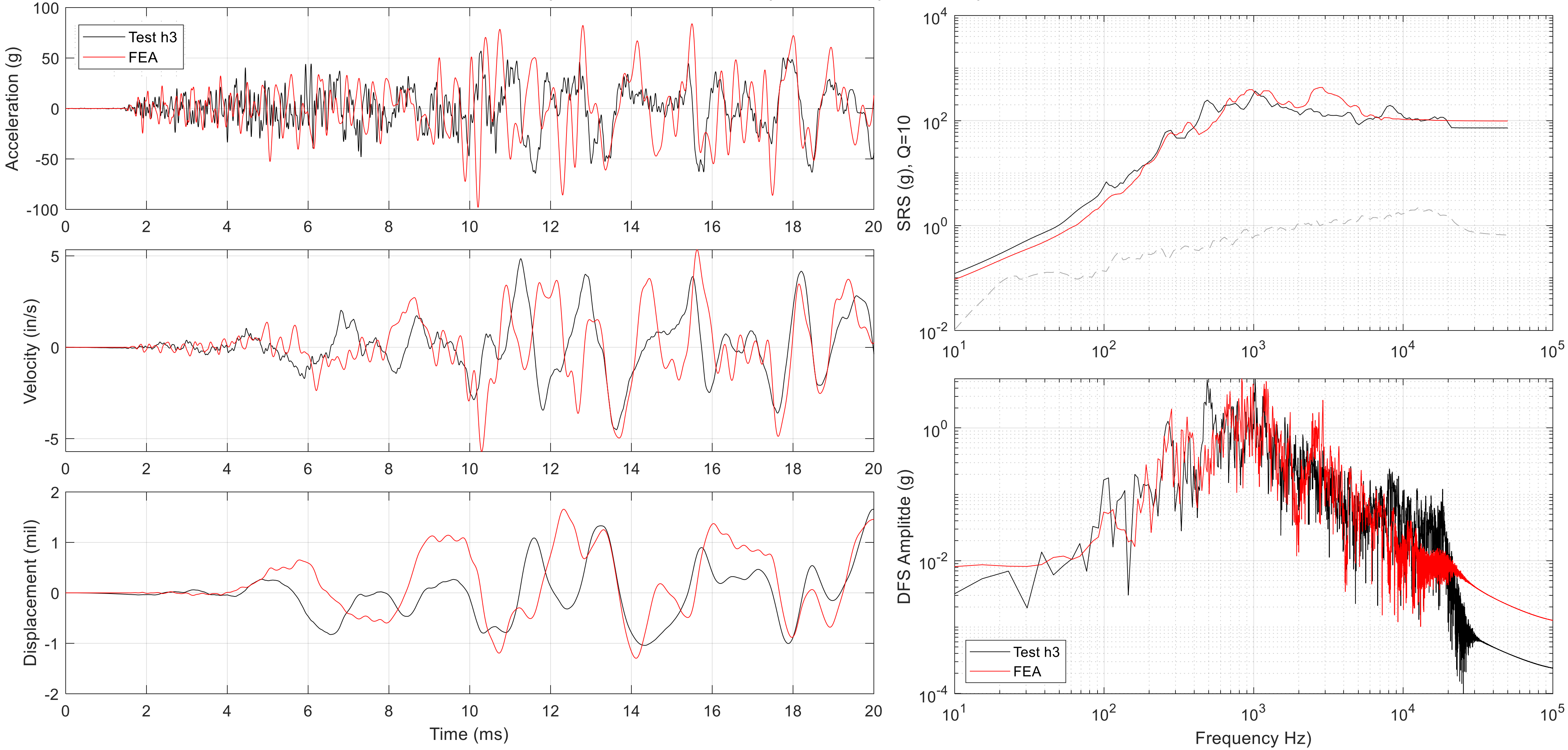
Tap Test 1 (+X Face Normal): A9X (Sta. 1.875): Source +X Face +Y Edge (10k)



quartus

SAMPLE RESPONSE: NORMAL ON CROSS BHD

Tap Test 1 (+X Face Normal): A28Z (Sta. 42): Cross Center

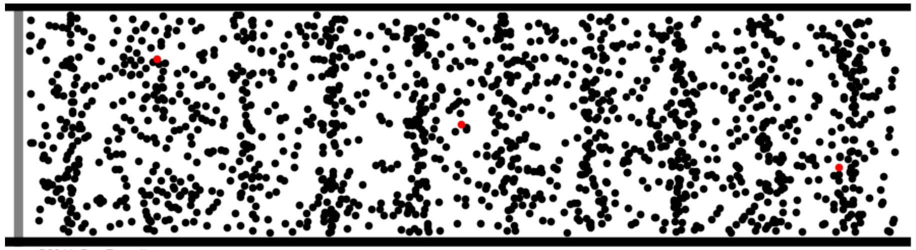


quartus

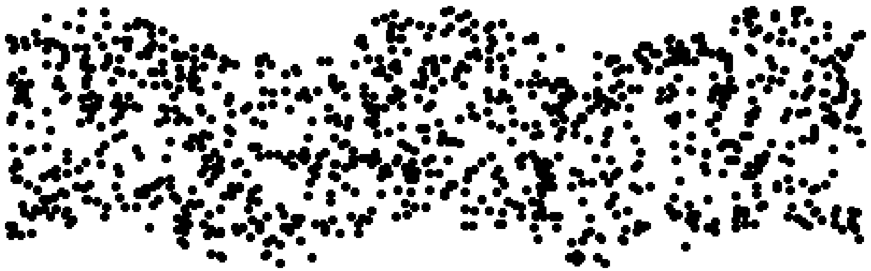
Expectations from Physics

Wave types display unique signatures

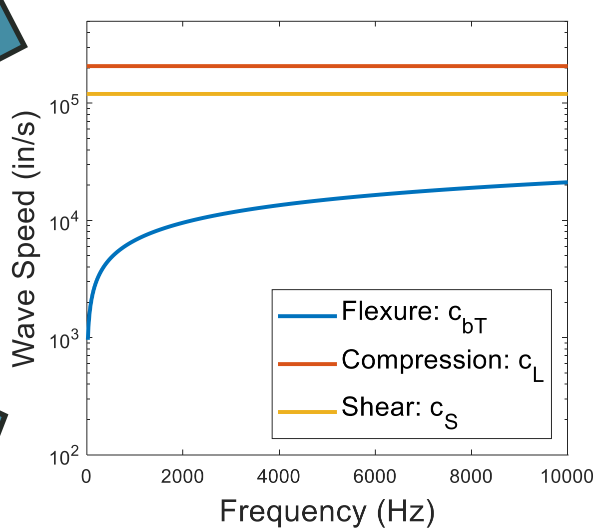
Longitudinal Waves – Compression

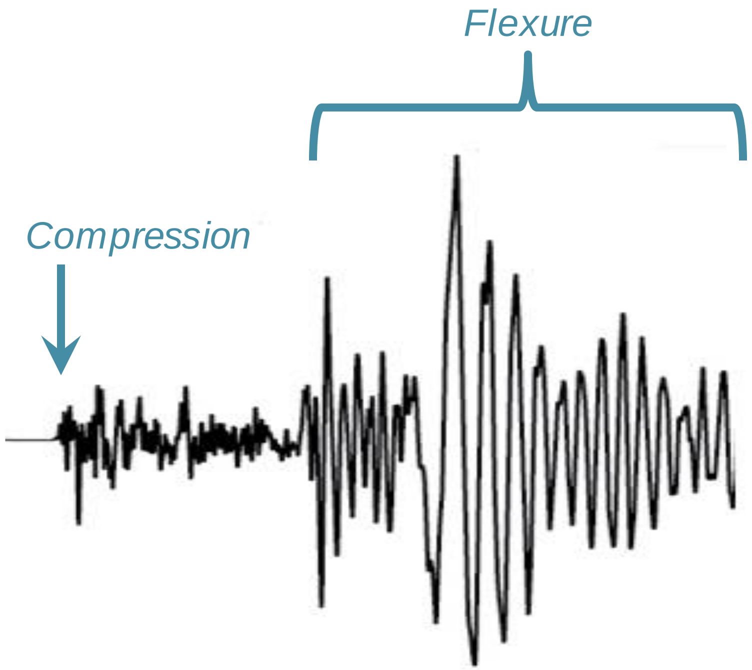


Transverse Waves – Flexure



D. A. Russell, 2016. The Pennsylvania State University
https://www.acs.psu.edu/drussell/demos/waves/wavemotion.html

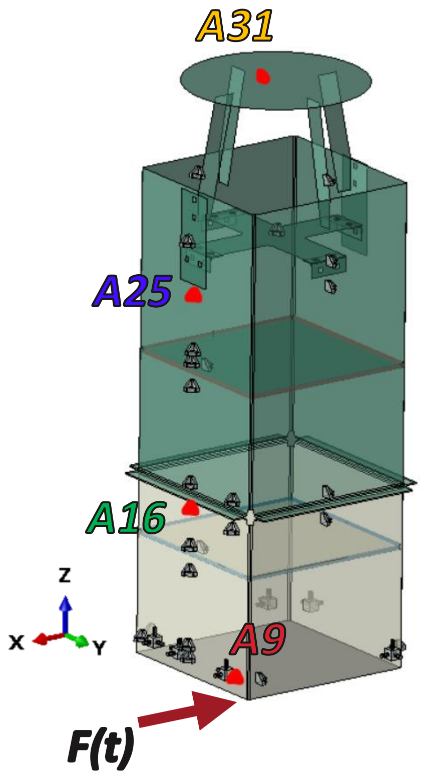


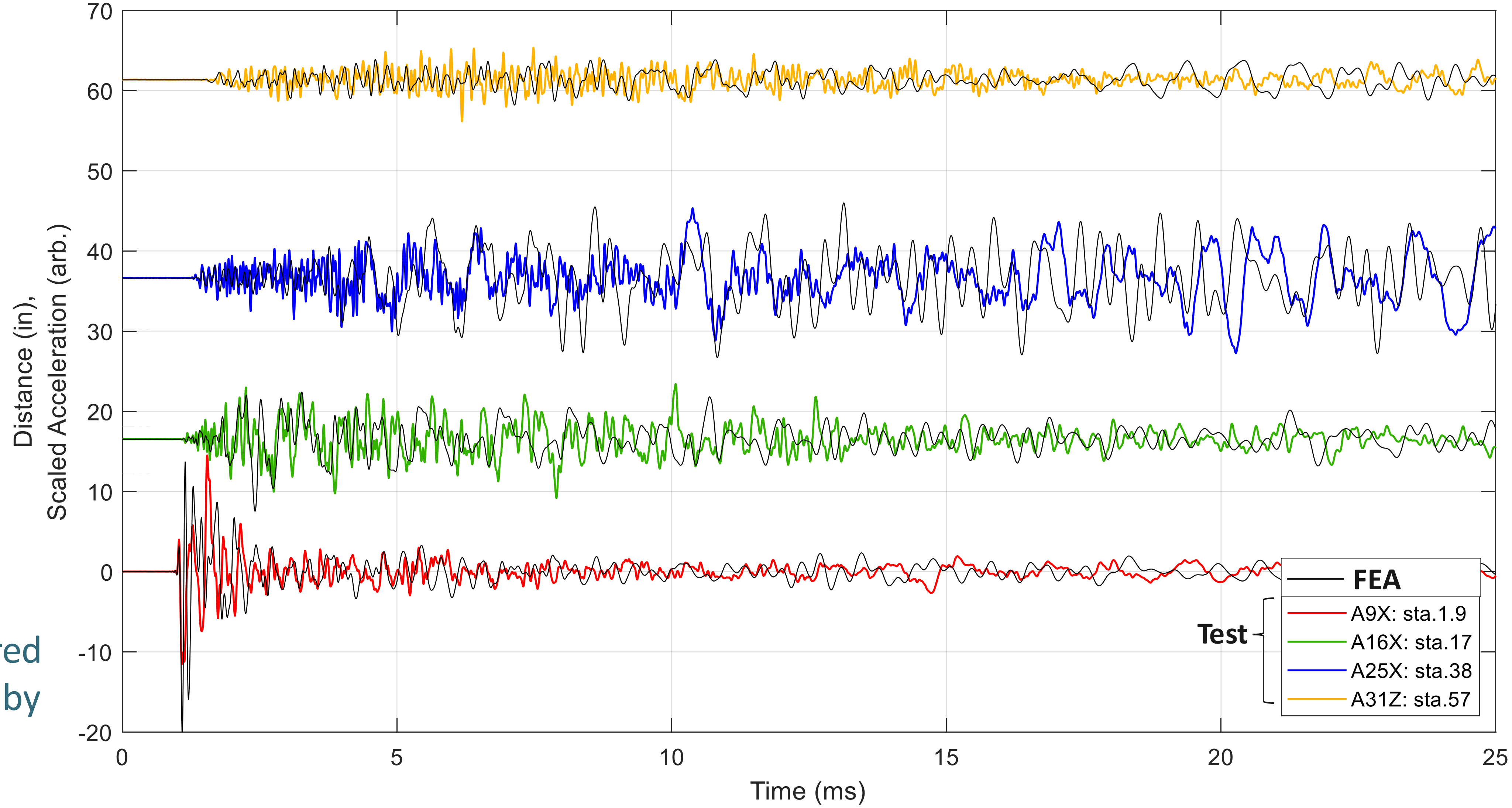


Michigan Technological University, 2024.
https://www.mtu.edu/geo/community/seismology/learn/seismology-study/

quartus

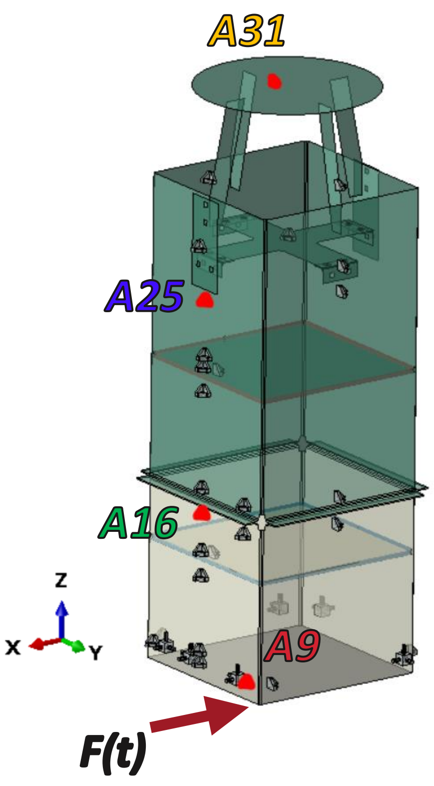
Wave Arrival Correlation - Normal Responses

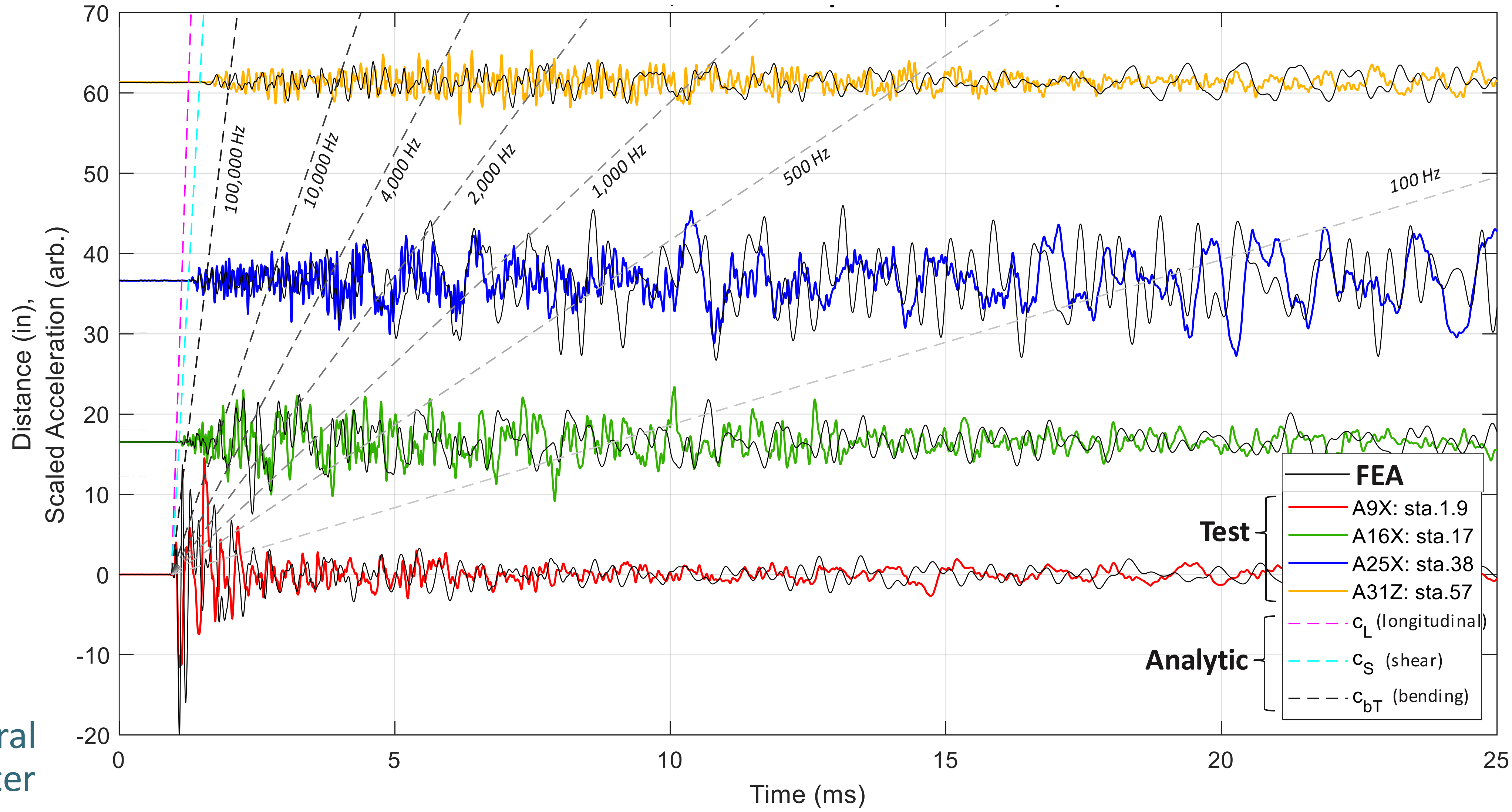




- Arranged measured & predicted data by distance

Wave Arrival Correlation - Normal Responses



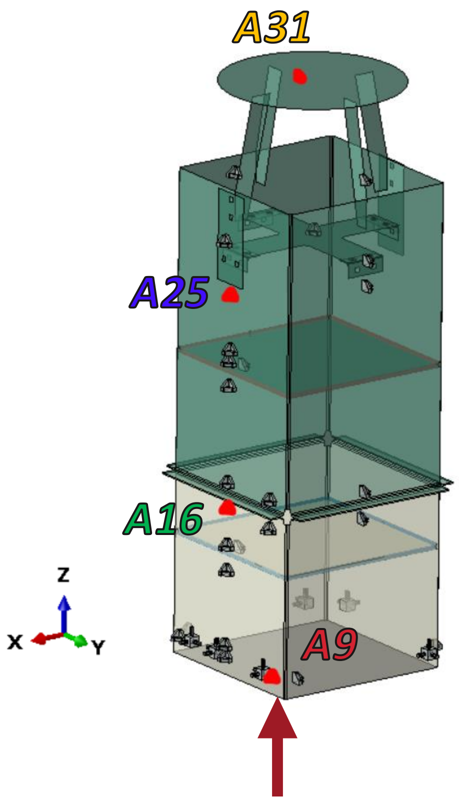


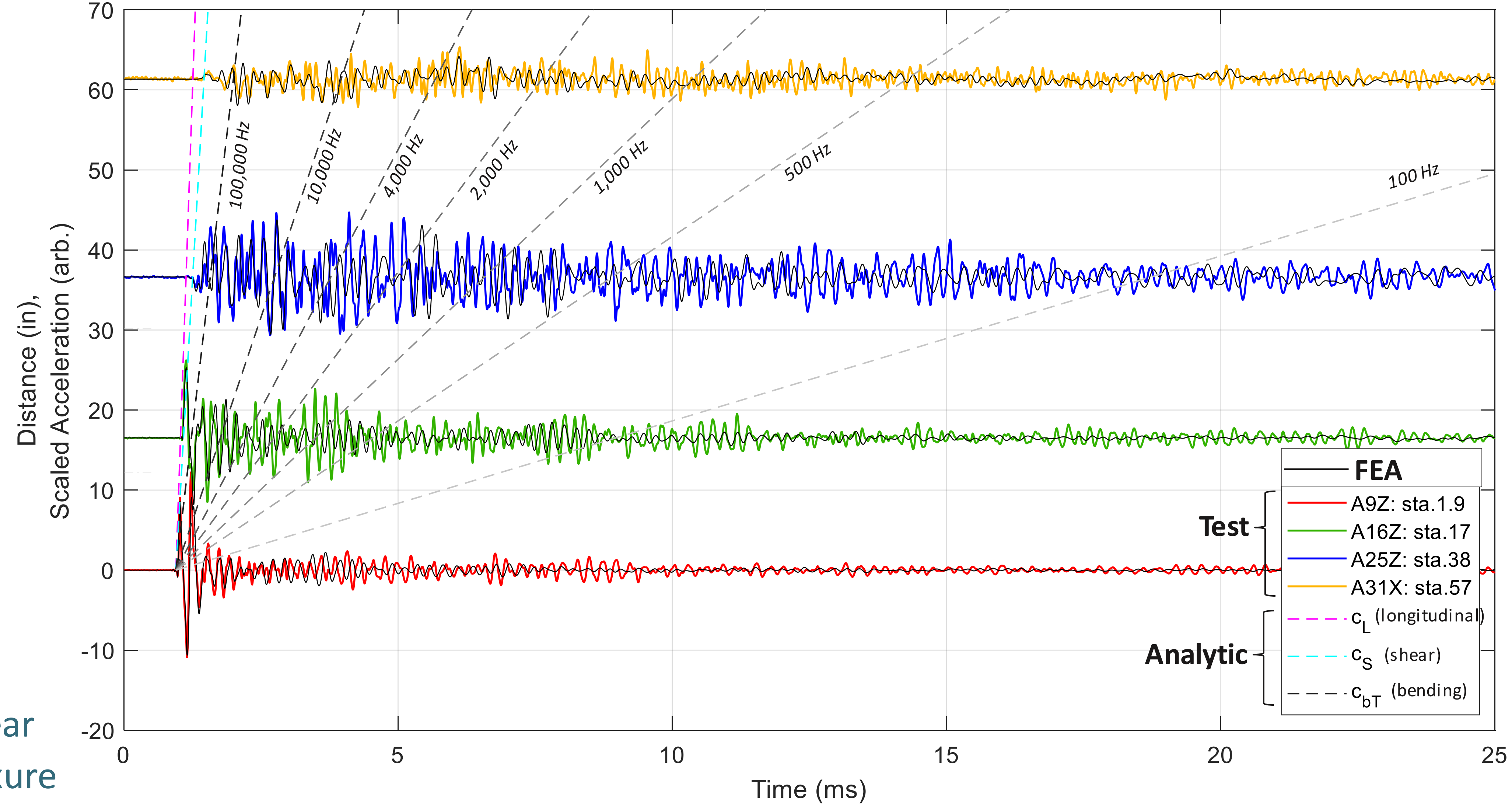
- Compression, shear arrive 1st
- Dispersive flexural wave arrivals later

quartus

Observe fundamental wave propagation driving transient signal waveforms

Wave Arrival Correlation - Axial Responses



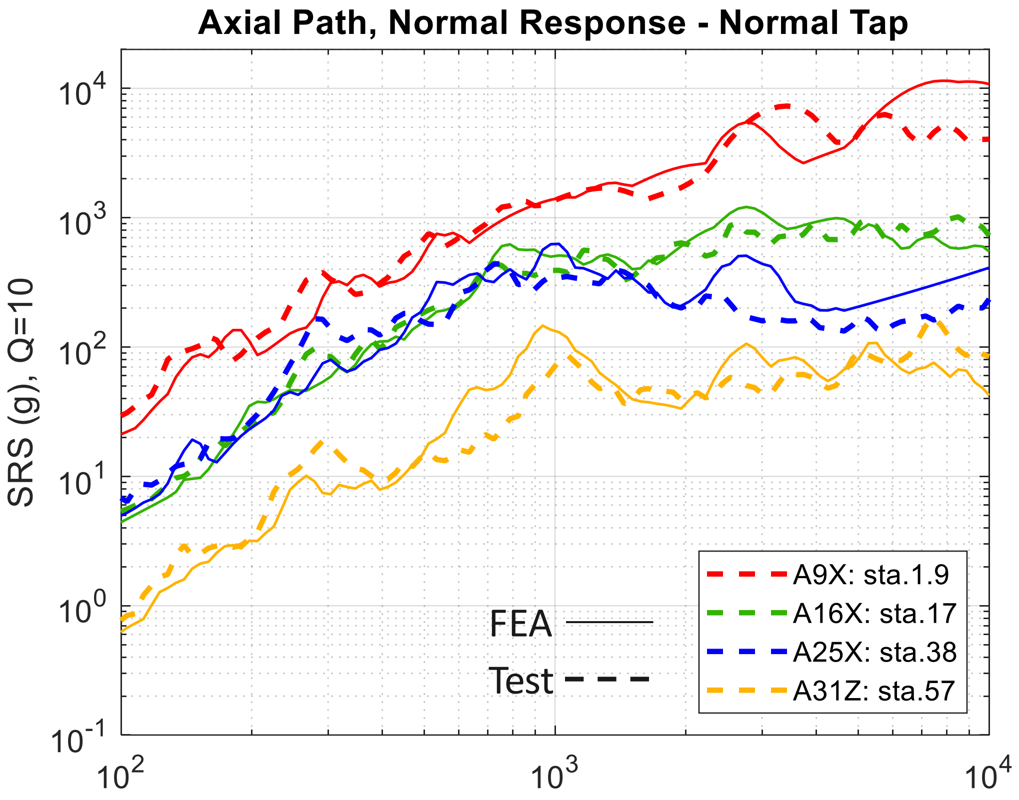


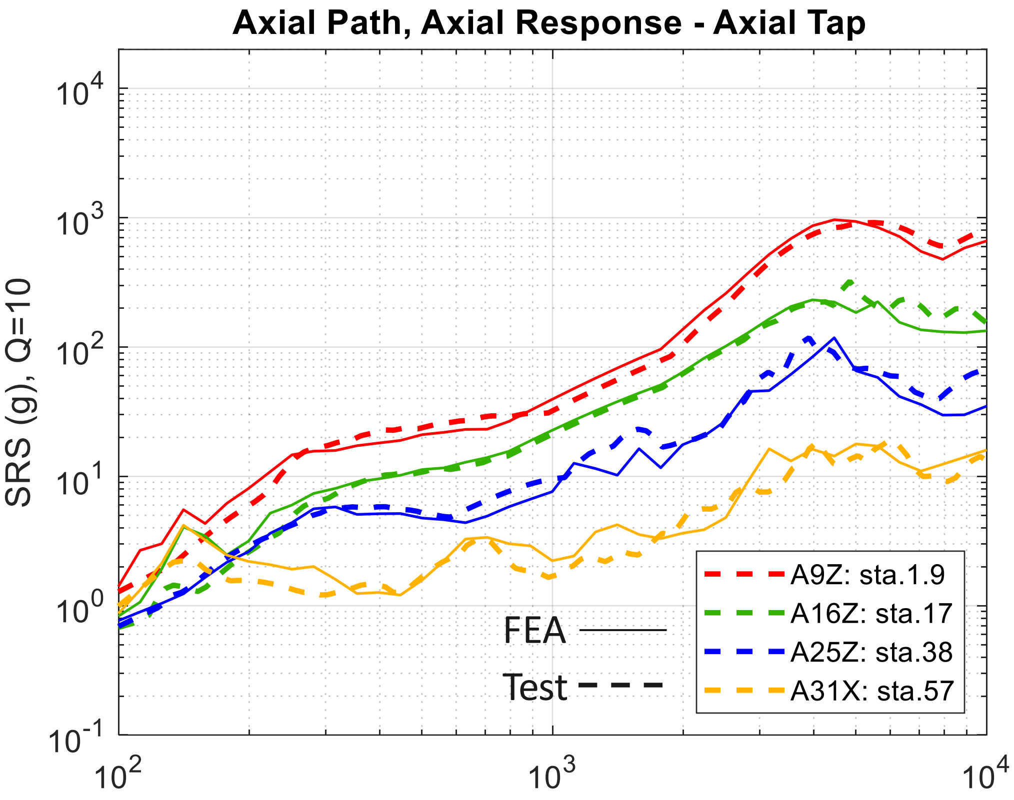
- Dominated by compression, shear
- Insensitive to flexure

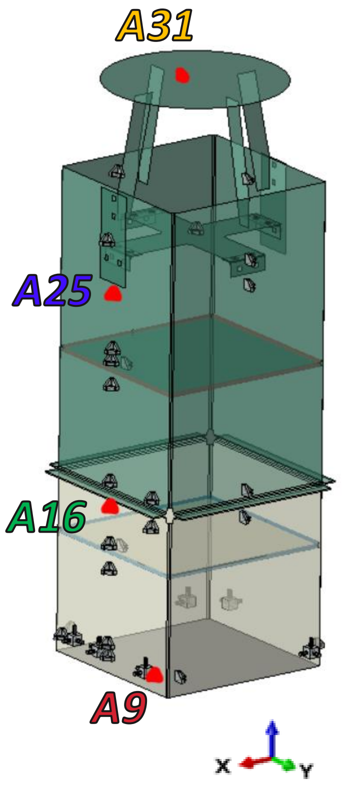
quartus

Observe fundamental wave propagation driving transient signal waveforms

SRS Response vs. Distance





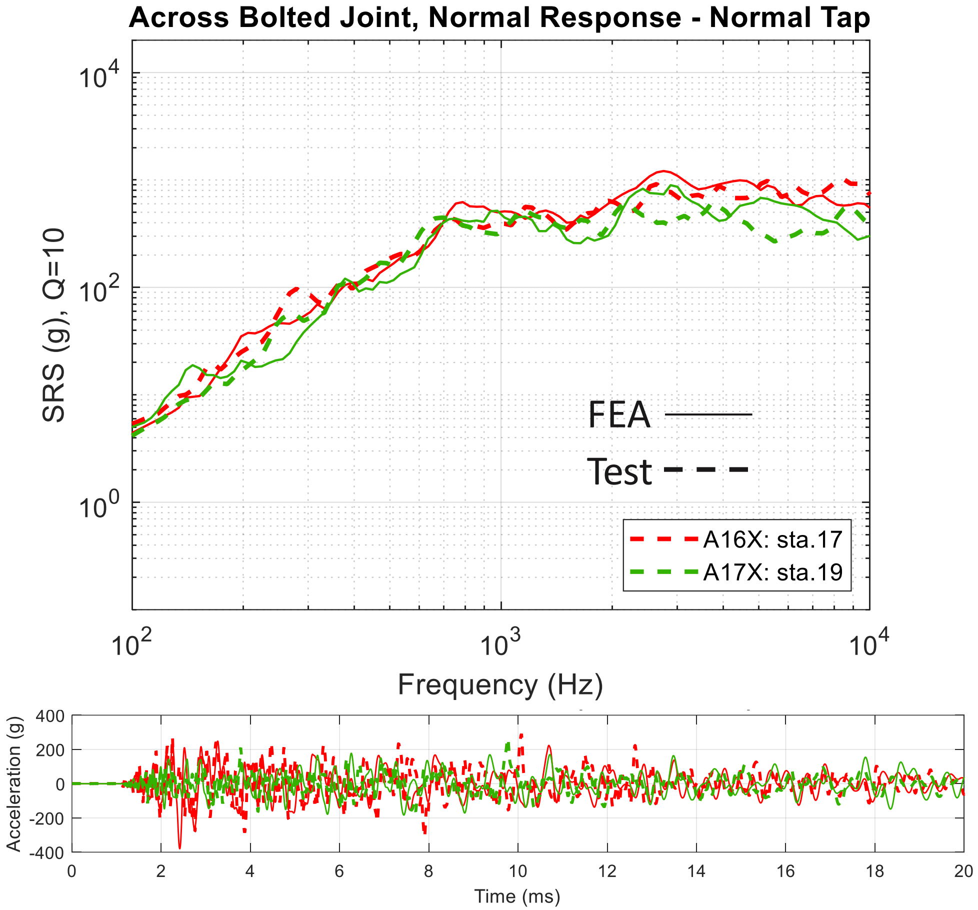


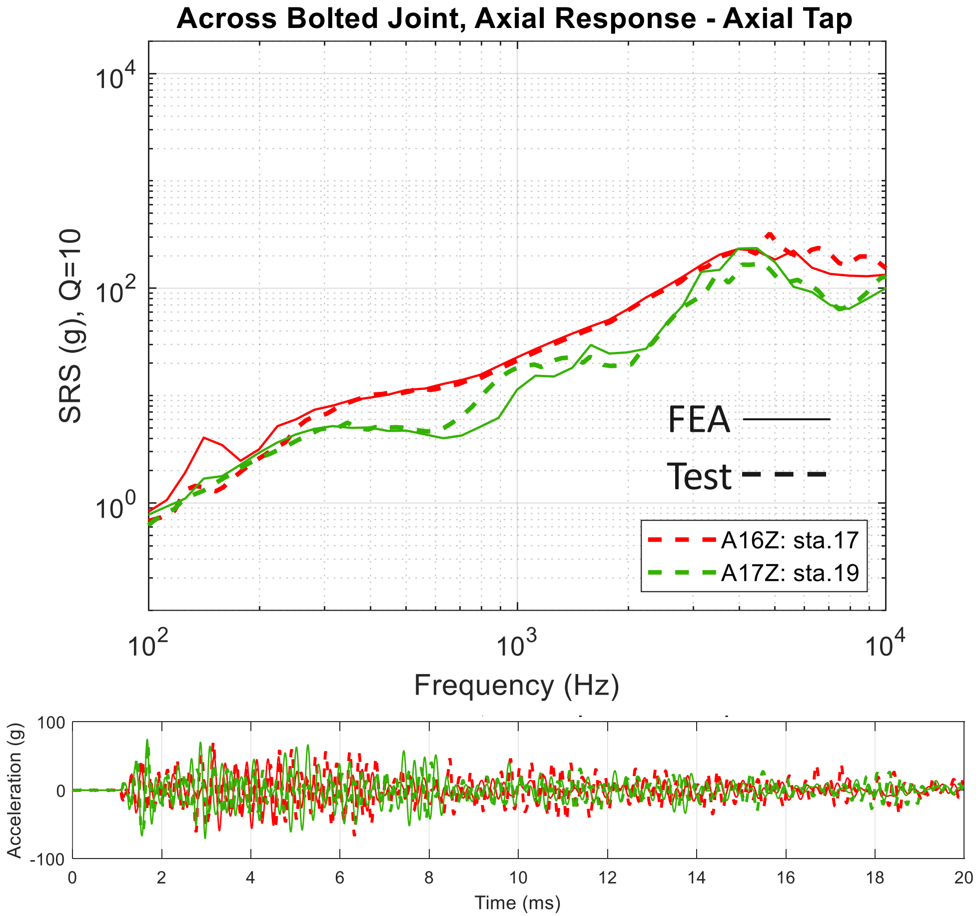
- Apparent SRS attenuation with distance, middle two locations are at comparable levels
  - Spans across multiple structural features, joints
- FEA predictions are quite good throughout - remarkable considering low modeling effort

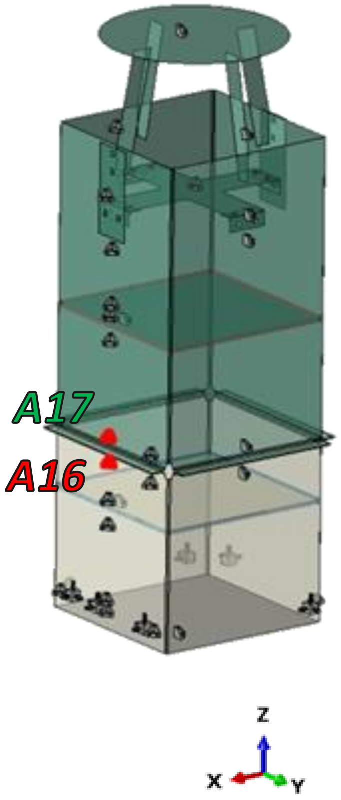
FEA captures trend & level, response differ greater than excitations alone

quartus

Response Across a Joint (J1: Bolted CRES/Al)





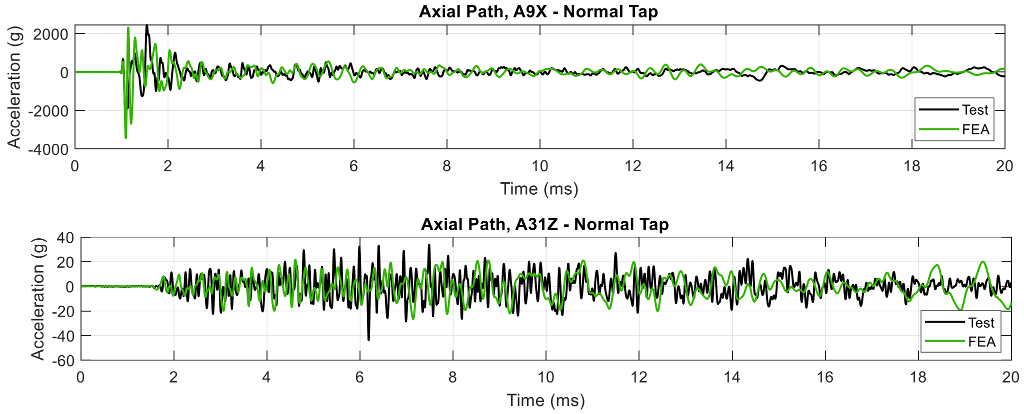


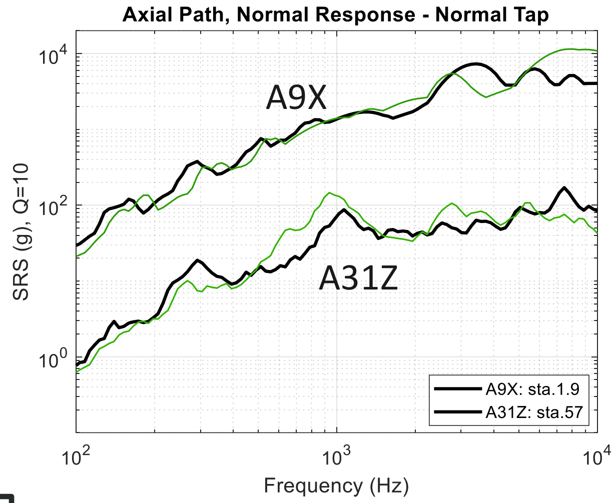
FEA prediction with linearized joints is remarkable – suggests lack of slip, nonlinearity

- Suggests some apparent attenuation across the joint - FEA & Test are consistent
  - No 'attenuation' seen in off-excitation-axis
  - Similar findings at welded bulkhead joints

quartus

Source & Far Field: FEA vs. Test

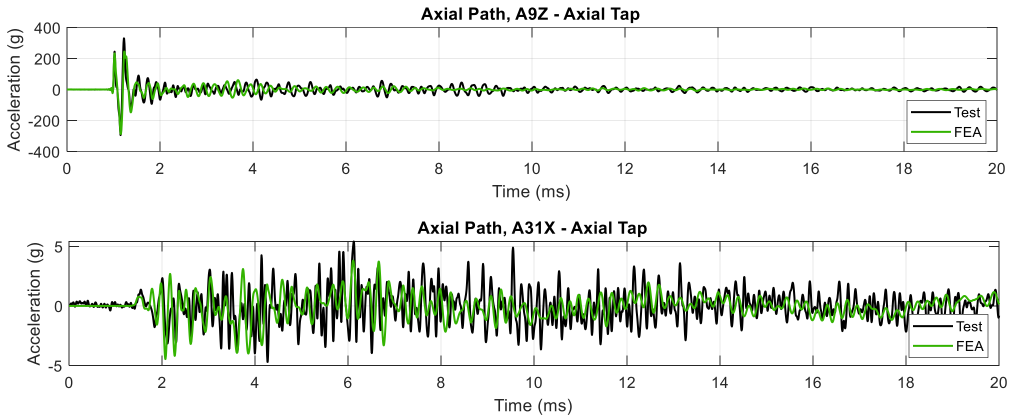


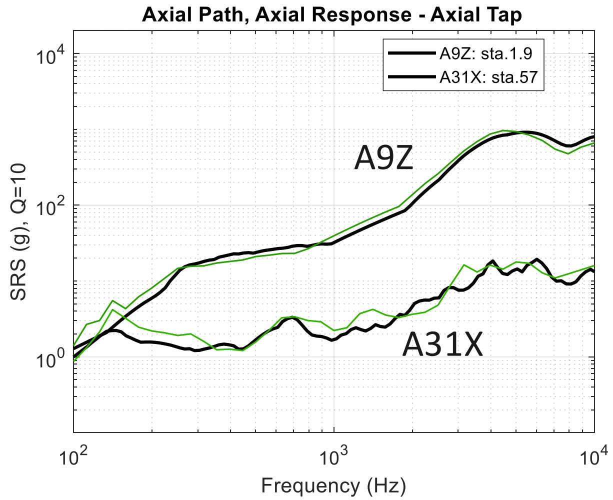


FEA provides a physical basis

FEA ——
Test ——

Empirical is SRS only

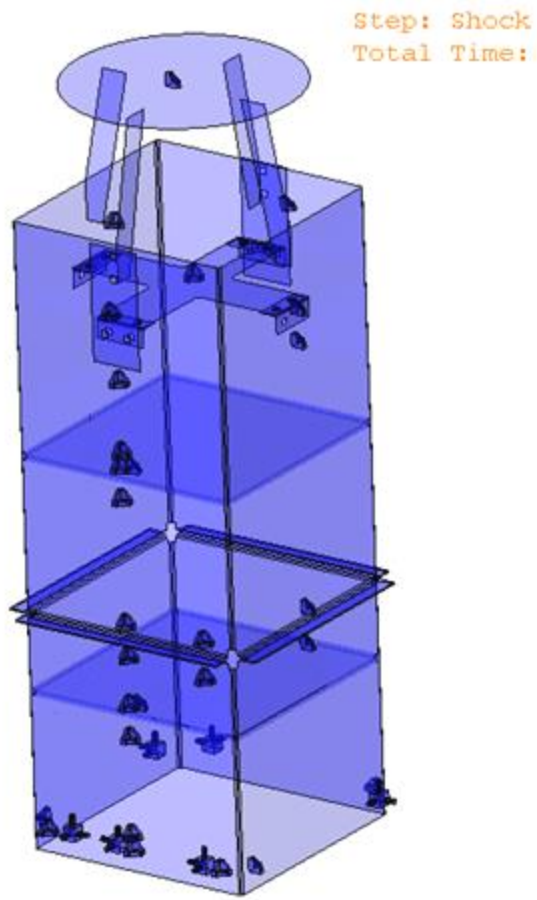




Accurate across the entire 'vehicle' → Underlying transient physics are missing from empirical scaling

quartus

CONCLUSIONS



- Low-effort application of explicit dynamics FEA to ShockSat performed very well – ***Demonstrated success now for SC & LV systems***
- Physics-based modeling is necessary to get it right, provides actionable insights
  - SRS alone is non-unique, incomplete
- Surprising accuracy attained with low-fidelity joint modeling here – ***Elaborate treatments may not always be needed***

Nature of shock excitation and wave propagation are important, credible methods need to consider this

quartus

ACKNOWLEDGEMENTS

- Sam Yunis (NASA ret.) for creating and sharing ShockSat

- Harry Armstrong & Luke Chiang (Quartus) for their help with some of the modeling