SAND2024-09377C

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Validating 3-axis mechanical shock environments with nonlinear dynamic models

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WCCM - PANACM
Vancouver, BC, Canada
July 23rd, 2024

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Outline

- Motivation
- Experimental Setup for Validation
- Model Development
- Results and Discussion
  - Shock Response Spectrum
- Conclusions

Motivation

- Components of aerospace systems are often subject to the pyroshock and other shock loads and, as such, must be qualified for those environments.
- Single-axis testing is a common qualification method, but it cannot perfectly reproduce the environmental loading.
- Three-axis tests can be complex and tedious to set up, so it is desirable to quickly iterate and design the test fixture computationally.

Pilot ejection

Stage separation

[Open source images]

https://www.wallpaperflare.com/search?wallpaper=ejection+seat

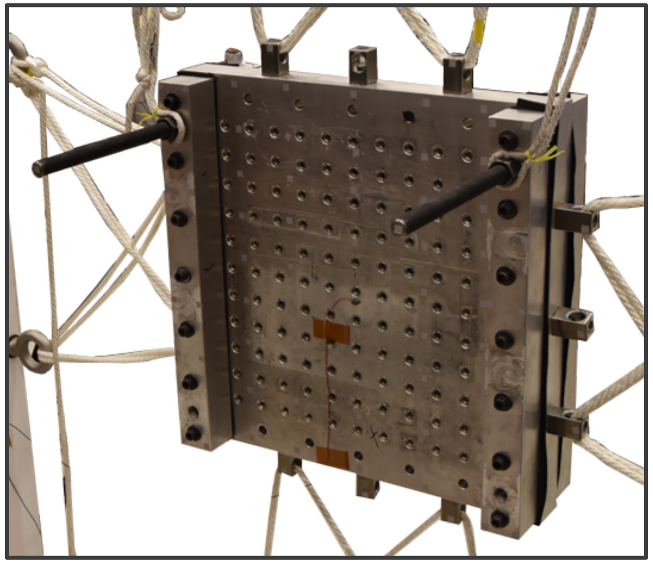
https://commons.wikimedia.org/wiki/File:BFR_at_stage_separation-2018_design.jpg

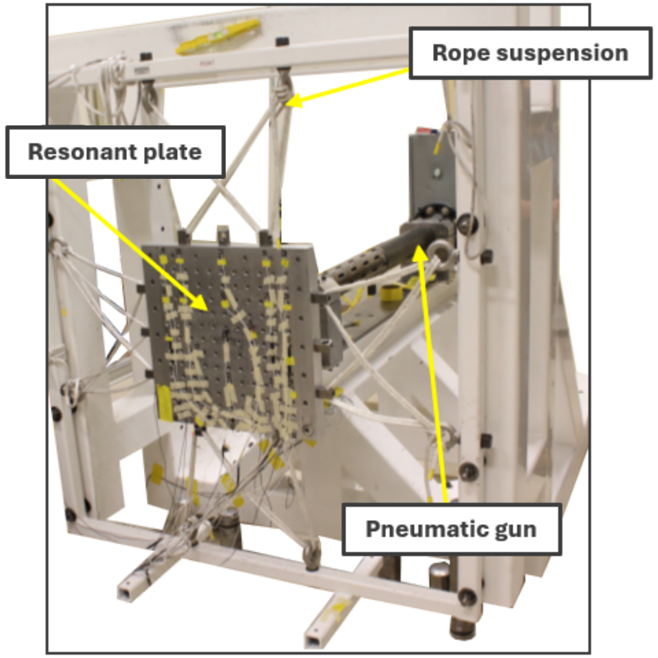
The Resonant Plate Test

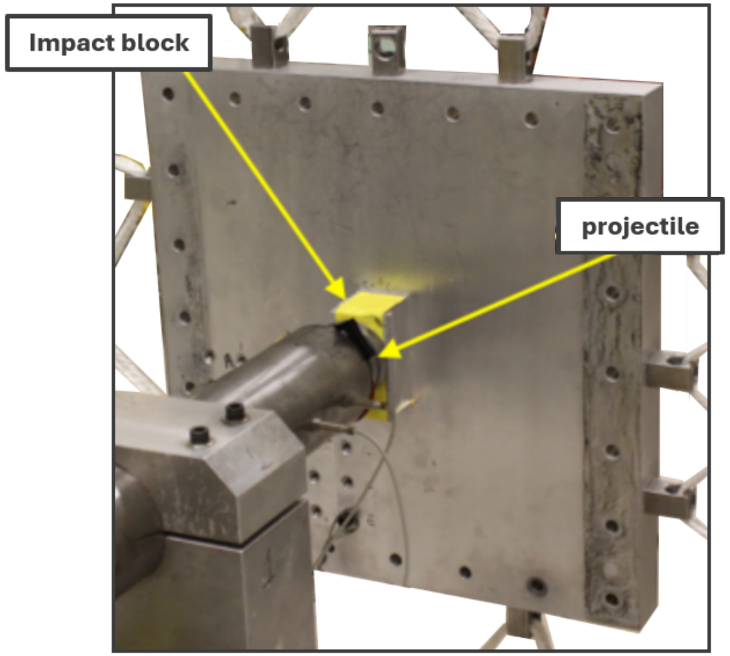
- A high-velocity projectile strikes the resonant plate and excites a response.
- Rubber and aluminum bars are added to tune the plates modes
- A felt material is attached to the face of the impact block to tune the impulse shape
- 24 accelerometers captured data for over 77 resonant plate shots with a variety of programmers, projectile sizes, and projectile speeds.

Summary of test data shots

Run Set Name	Test Runs	Pressure (psi)	Felt Thk (in)	Projectile Length (in)	Average Projectile Speed (ft/s)
Set 14	[14:17]	10	1/8" Grey	6"	21.5
Set 21	[21:27]	14	1/8" Grey	6"	28.1
Set 28	[28:31]	10	1/8" Grey	6"	21.3
Set 32	[32:35]	10	1/2" Grey	6"	21.4
Set 36	[36:39]	20	1/2" Grey	6"	35.7
Set 41	[41:47]	20	1" Grey	6"	36.0
Set 48	[48:51]	40	1" Grey	6"	53.5
Set 54	[54:57]	50	1" Grey	6"	59.8
Set 58	[58:61]	20	1" Grey	12"	23.9
Set 62	[62:65]	40	1" Grey	12"	37.1
Set 66	[66:68]	60	1" Grey	12"	46.1
Set 69	[69:72]	15	1/2" Grey	12"	19.5
Set 73	[73:76]	25	1/2" Grey	12"	27.8
Set 78	[78:81]	35	1/2" Grey	12"	34.1
Set 82	[82:85]	15	1/8" Grey	12"	19.1
Set 86	[86:91]	25	1/8" Grey	12"	27.5

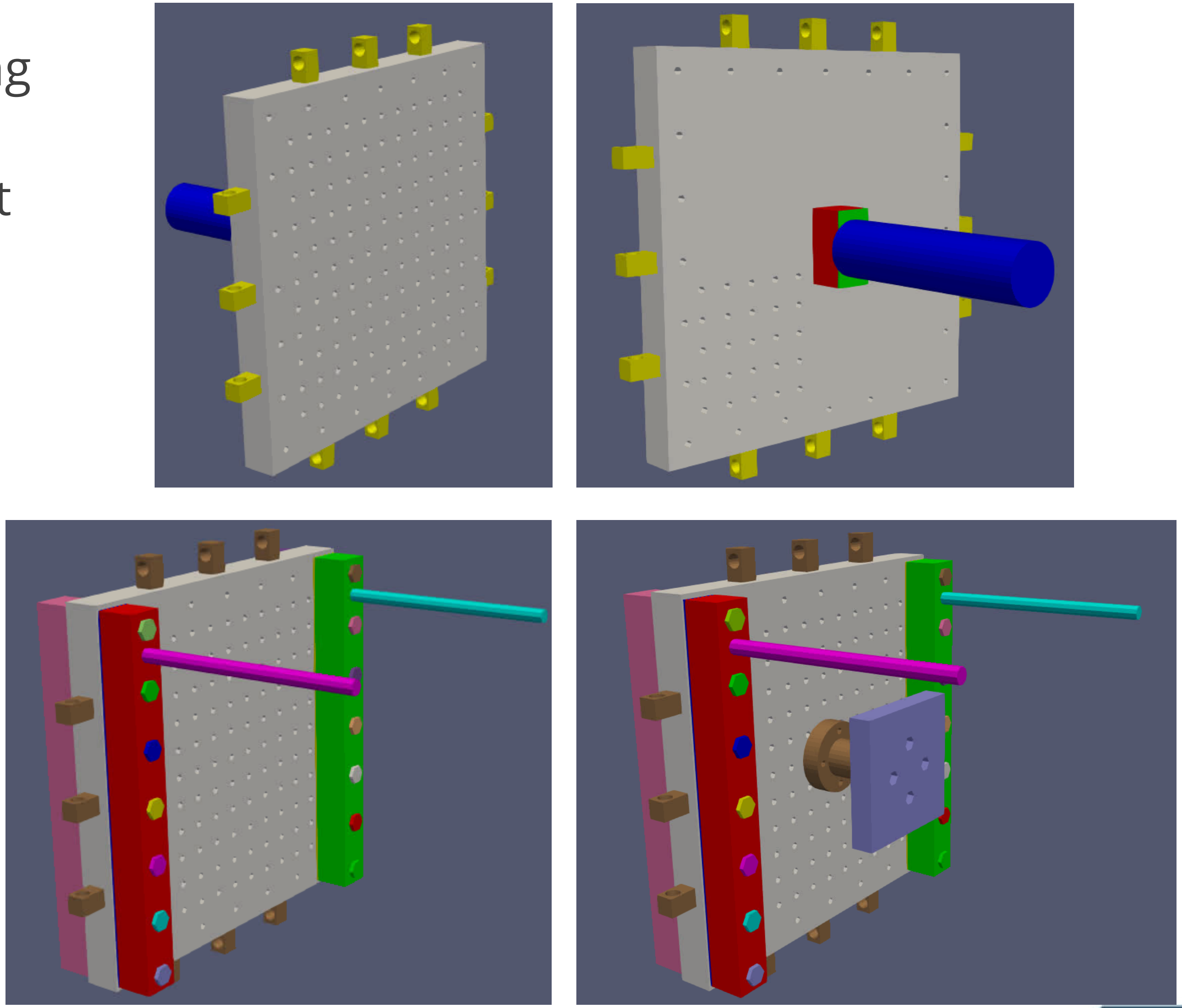






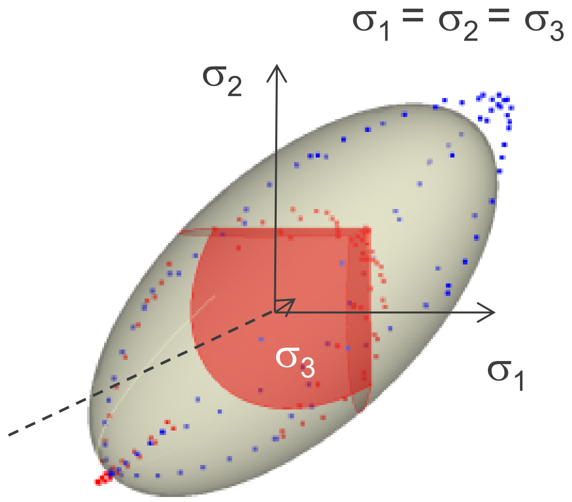
Model Development

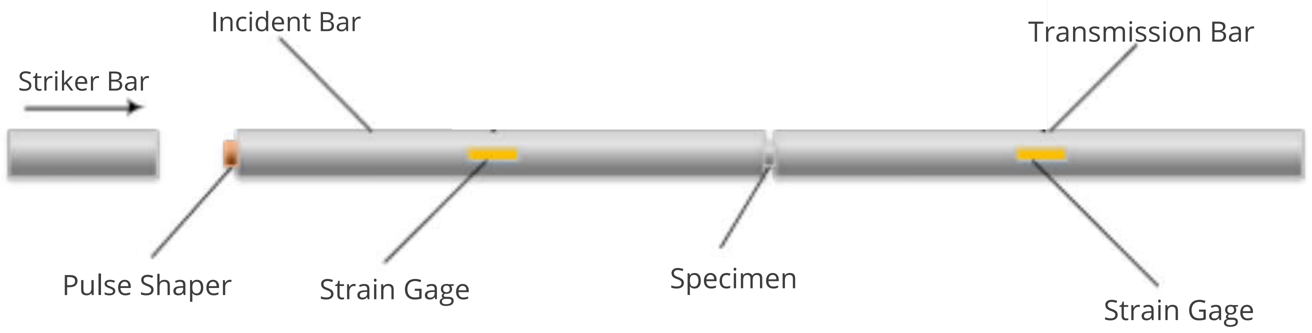
- The test fixture has been computationally modeled, including surface holes for mounting the unit under test.
- The nonlinear model is simulated with explicit dynamics with the following features:
  - Prescribing an initial velocity on the projectile
  - Contact and friction
  - Large deformations
  - Nonlinear material models for felt, rubber, and elastic-plastic behavior
- To validate the model, the fixture is simulated in stages to not propagate errors into the components response:
  - Bare plate
  - Plate with damping
  - Plate with damping and component

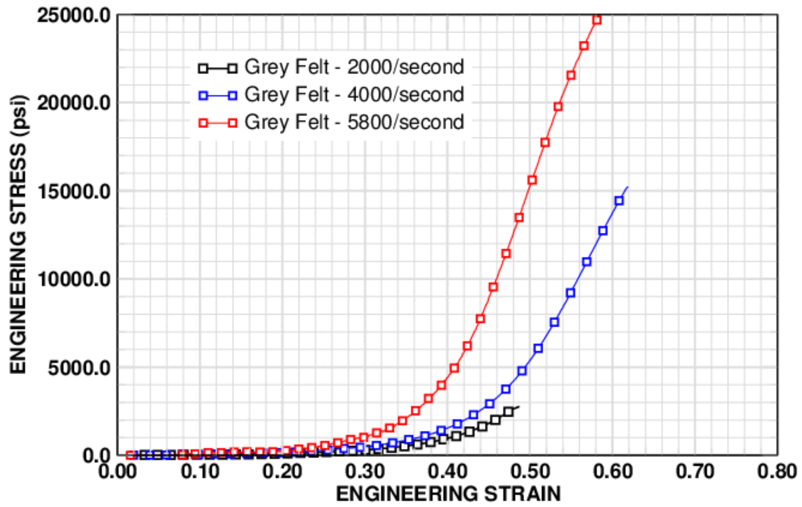


Split-Hopkinson Bar Experiment for Material Parameters

- Since felt is a porous material, it can withstand a lot of compression before large amounts of stress are introduced.
- The felt will fail quickly under tension, behavior that is captured by a foam model with an ellipsoidal yield surface truncated by red damage surfaces for loading in tension.
- The Split-Hopkinson bar induces a compression wave to move through the material specimen.
- By measuring the strain through the bars, the Young's modulus of the material can be approximated.

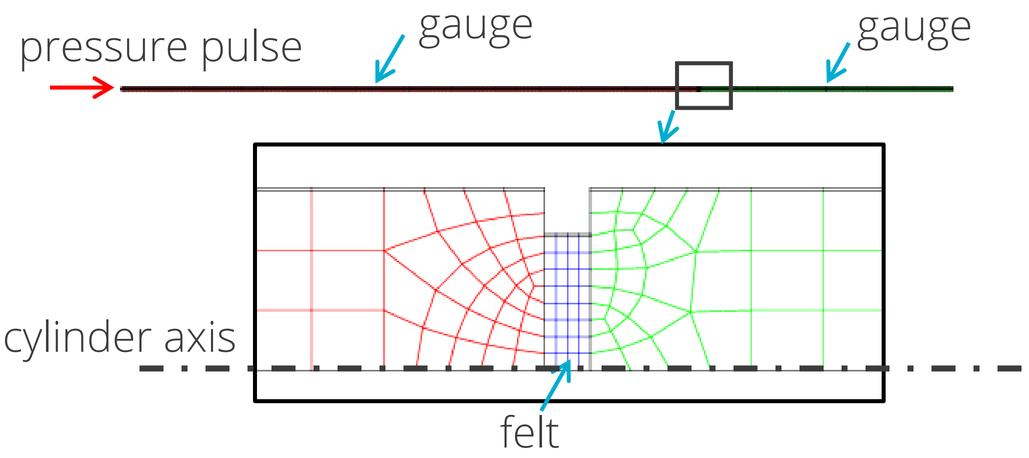


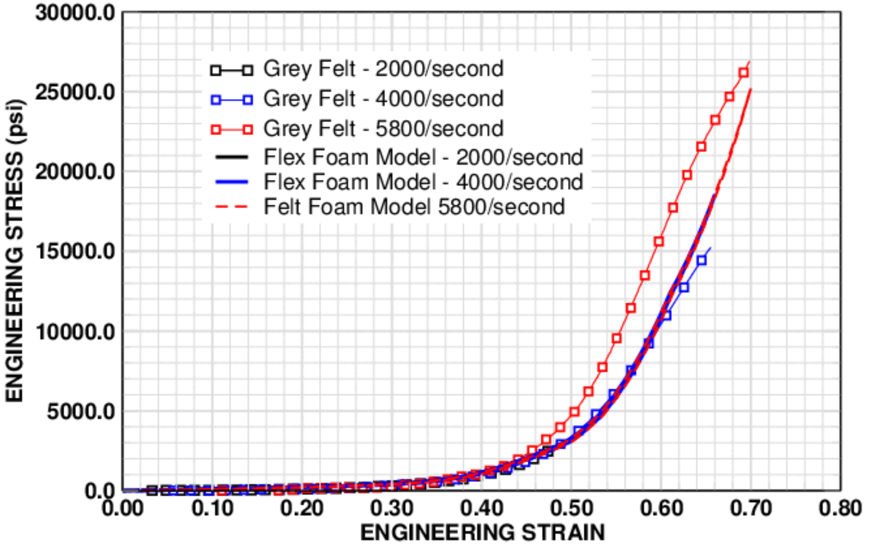


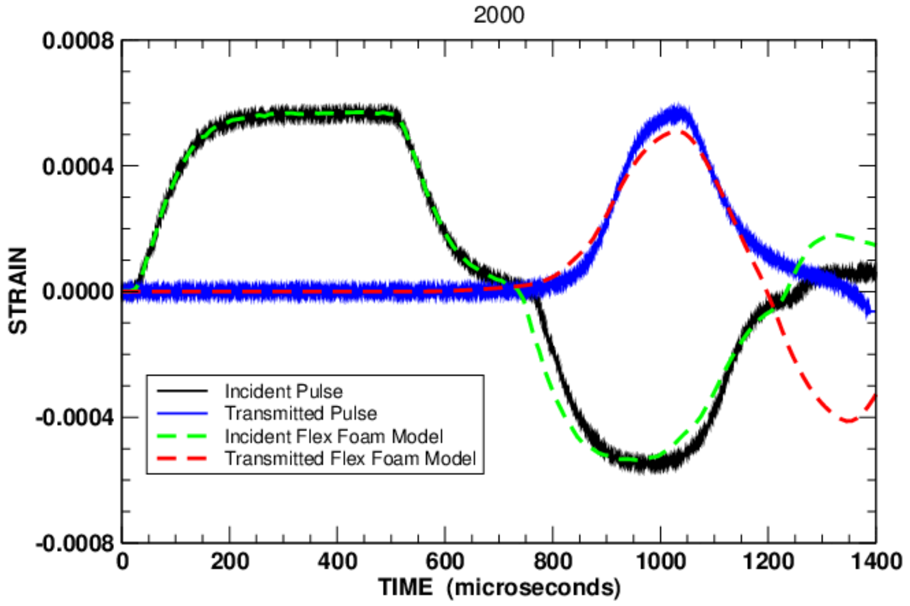


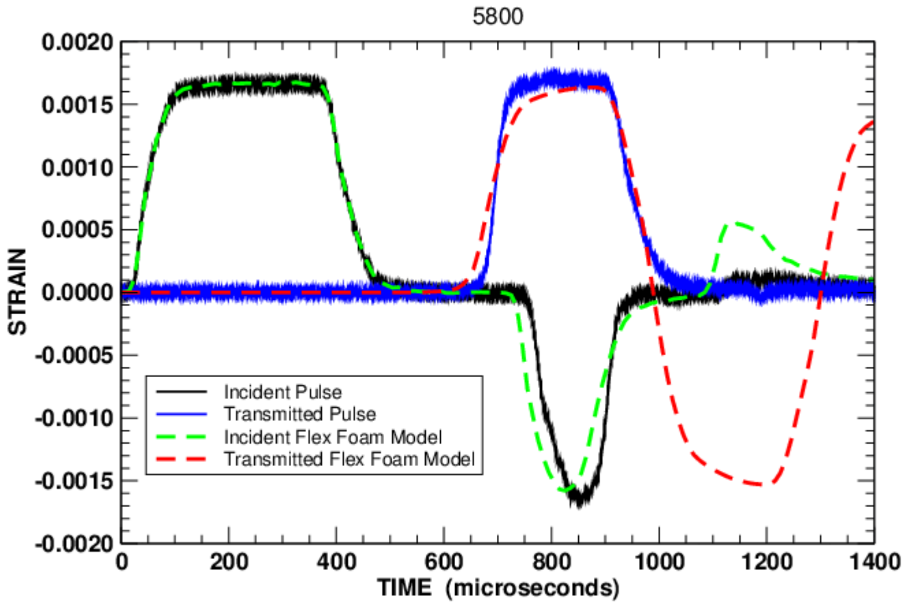
Material Model Validation

- Once the material parameters were approximated, the Hopkinson bar experiment was simulated to validate the foam model used for felt.





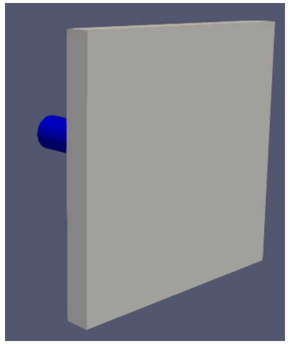


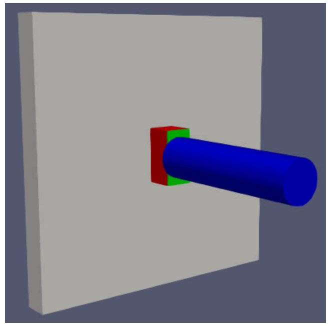


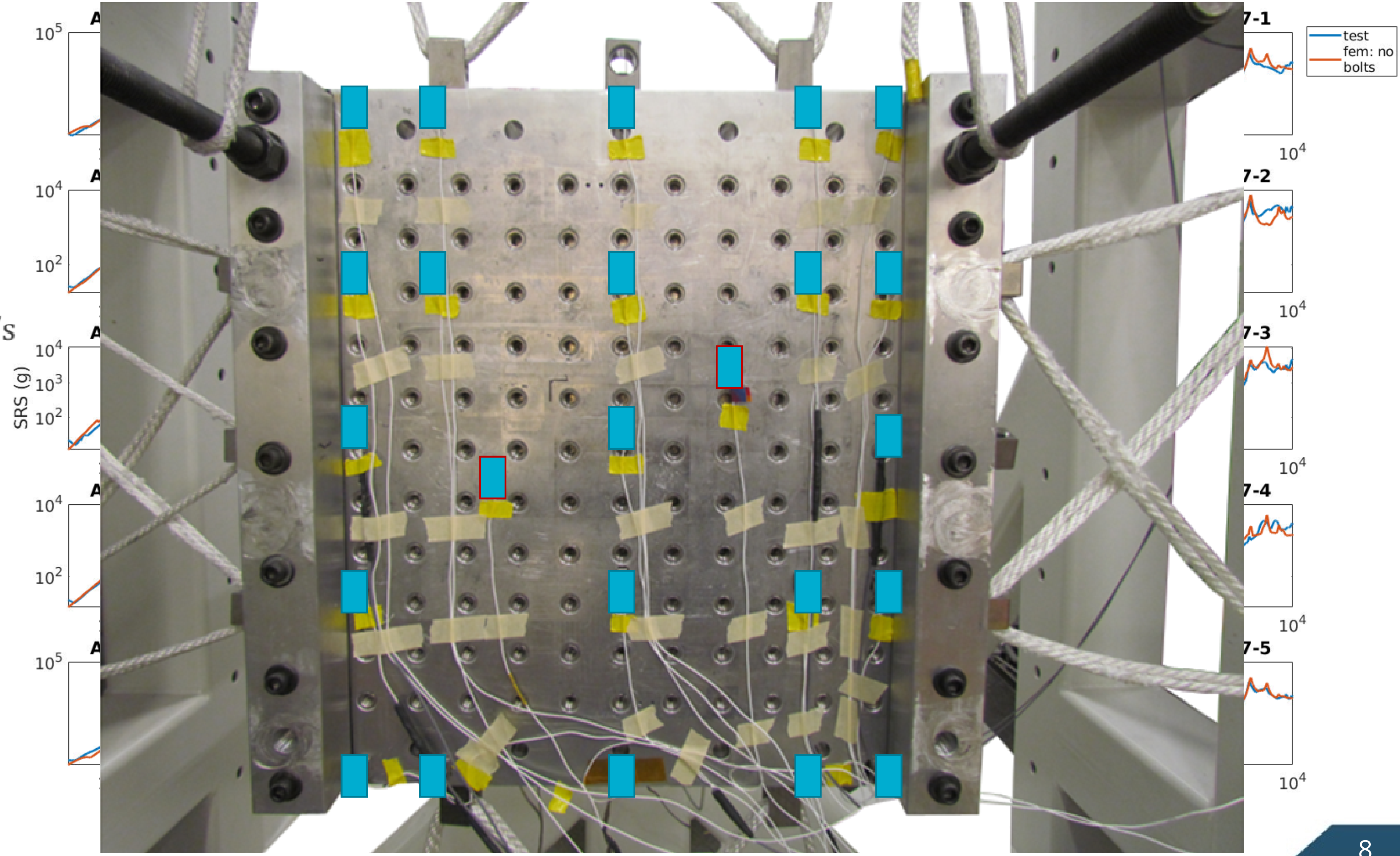
Results Comparison: Bare Plate with No Mounting Holes

Test configuration:

- Plate with no damping or components
- 12″ projectile
  - $v_i = 20.2\ \text{ft/s}$
- 1/8″ felt

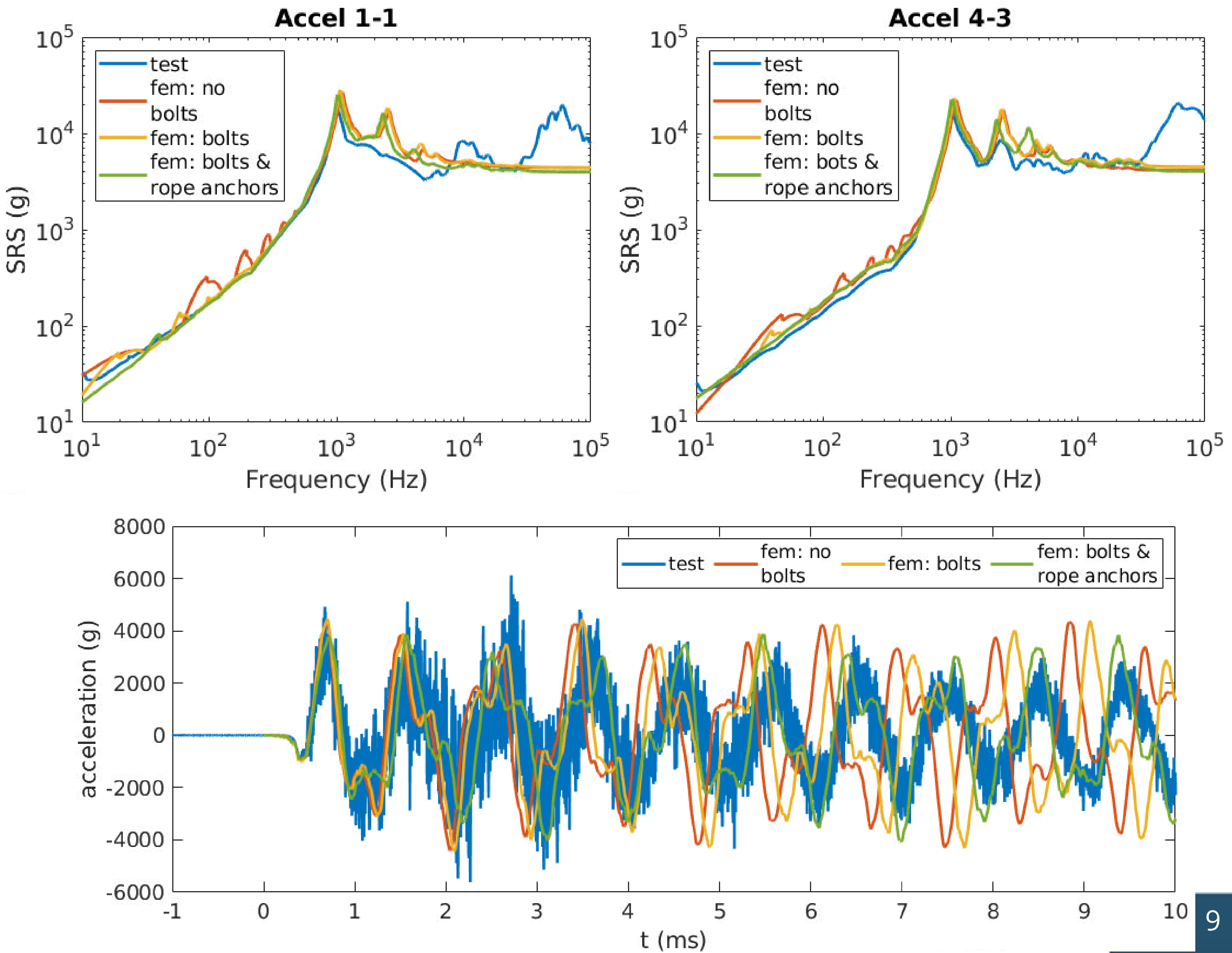






Results Comparison: Bare Plate

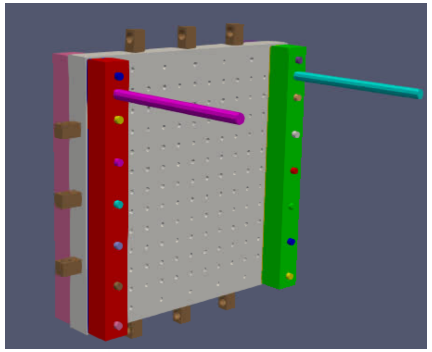
- Adding the mounting holes for the bolts had a minimal effect on the response.
- The addition of the rope anchors reduced the frequency to better match the peaks in the SRS.
- Through the first 10 ms of the time history, the configuration with the rope anchors and the bolt holes matches the response of the test excellently.

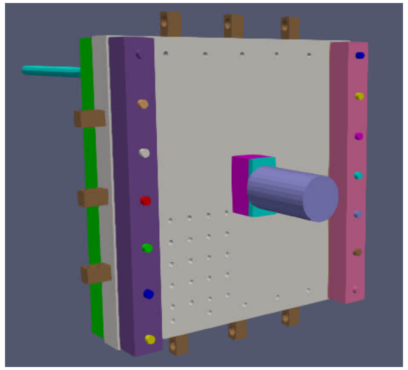


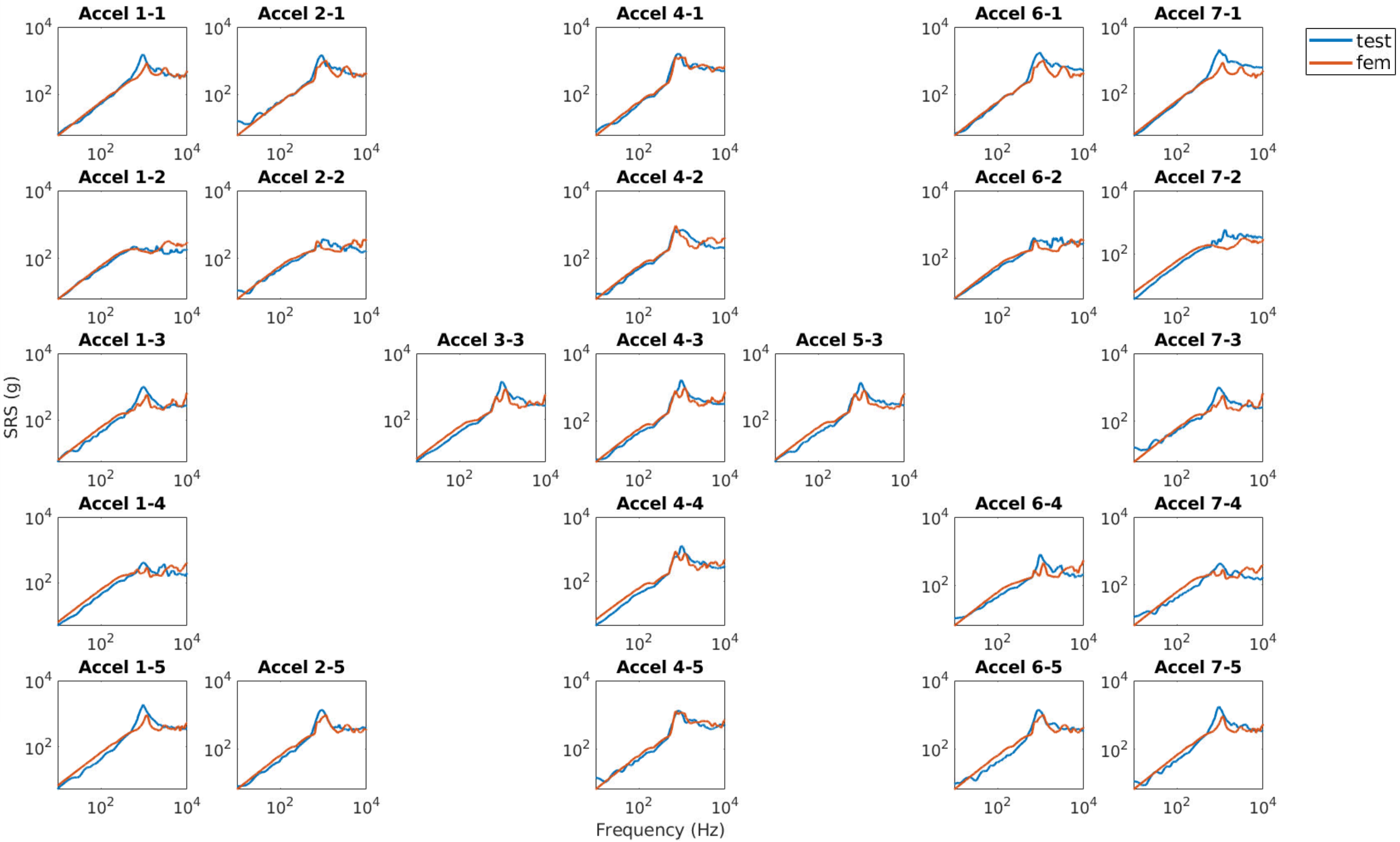
Results Comparison: Plate with Damping Bars

Test configuration:

- Plate with damping but no components
- 6″ projectile
  - $v_i = 19.5\ ft/s$
- 1/2″ felt

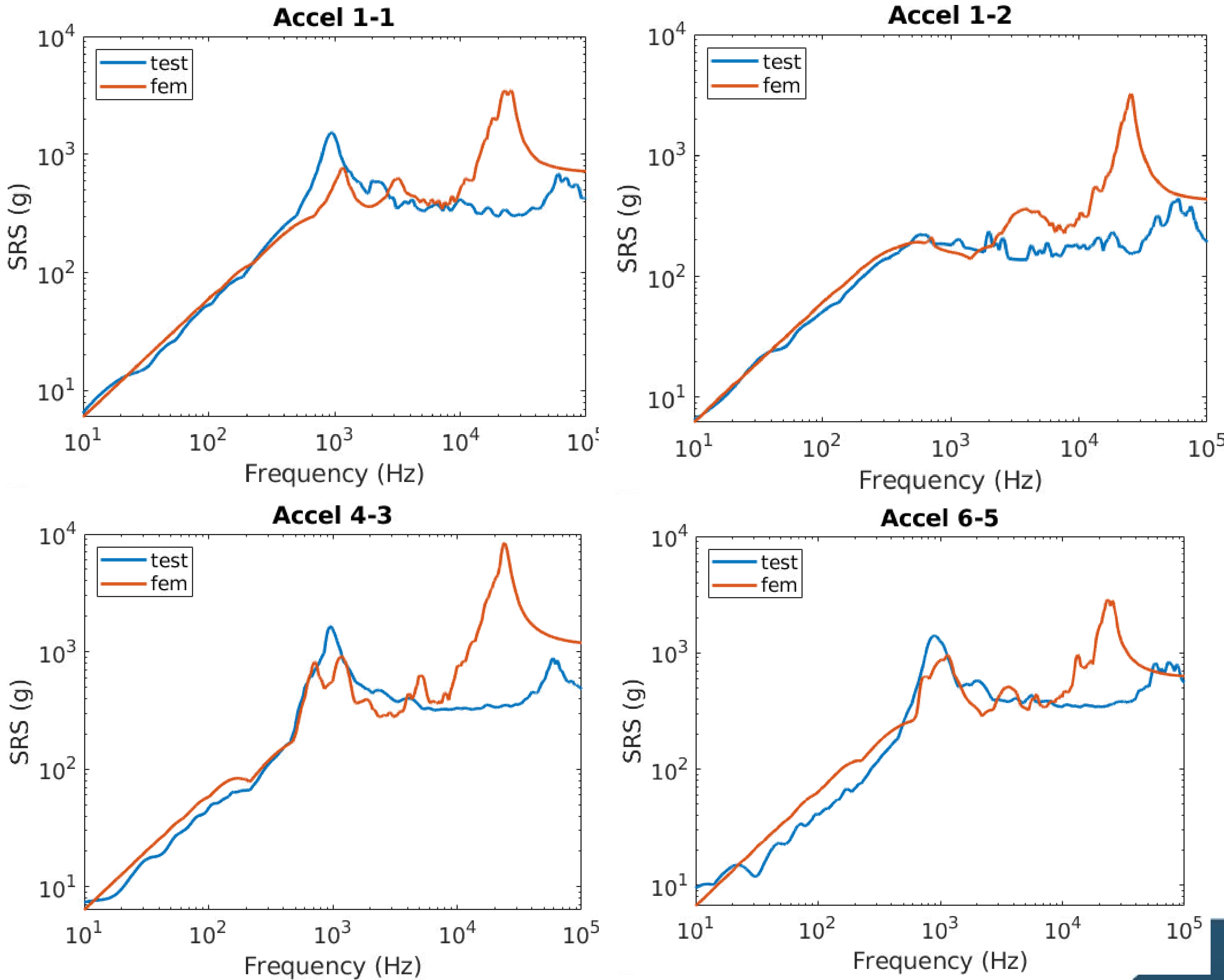






Results Comparison: Bare Plate with Damping Bars

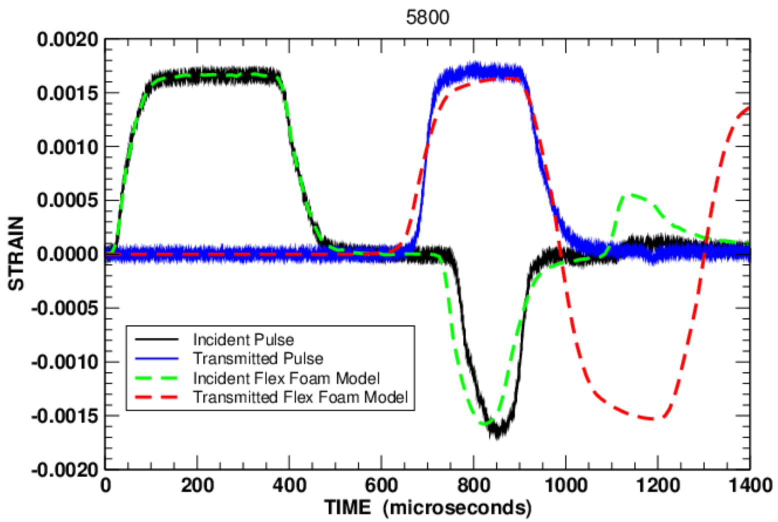
- First resonant peak generally matches frequency band, but some discrepancies in amplitude.
- High-frequency amplitudes still present in test at ~60 kHz.
- Large amplitudes occur in the FEM around 25 kHz.
  - What causes this?
    - Damping bars/rubber?



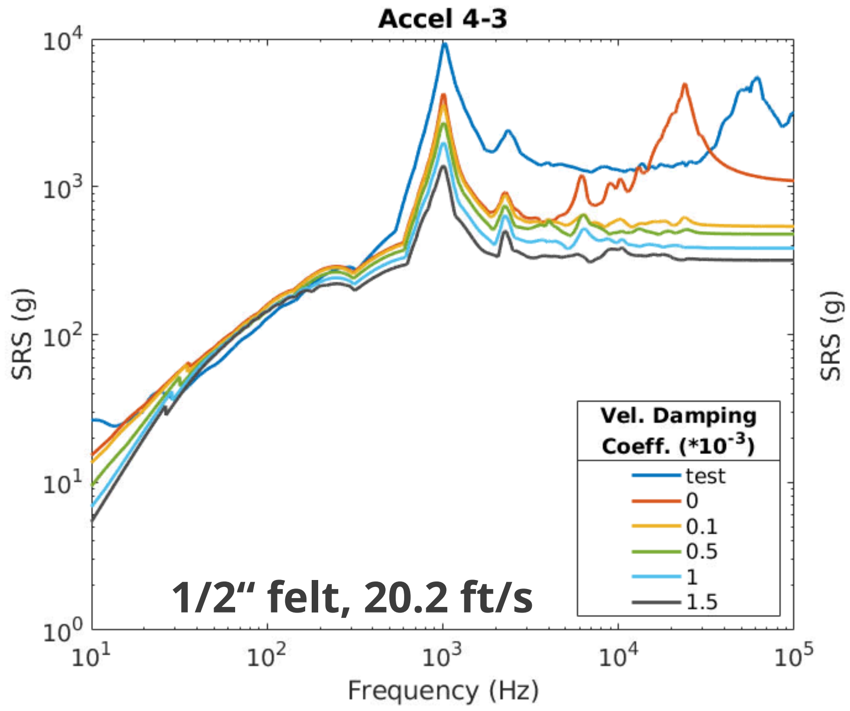
Applying Velocity Damping to the Felt Volume

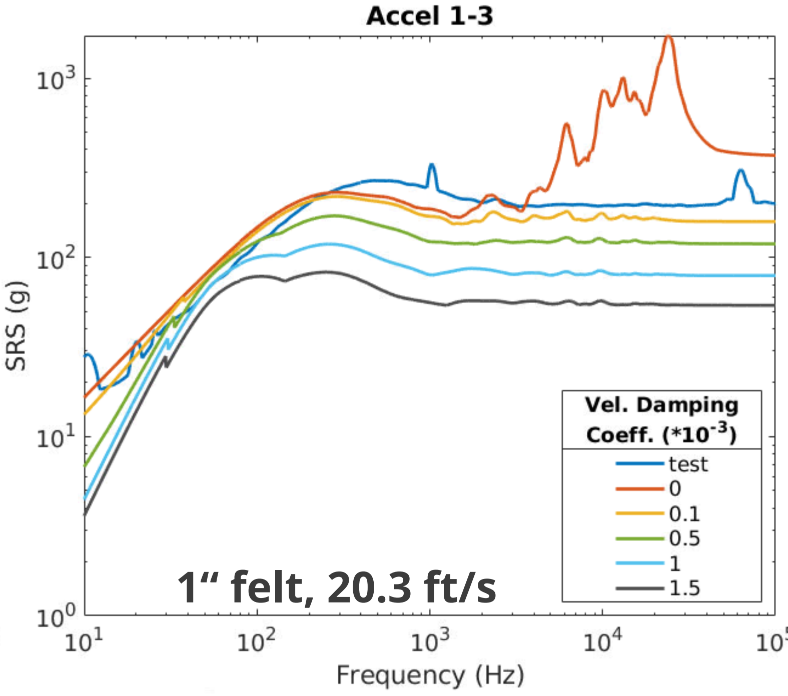
- The change in felt thickness was found to be the cause of the high-frequency amplitude in the simulation.
- The felt material model contains reflection waves in the Hopkinson bar simulation that the test does not.
- Adding a small velocity damping eliminates the high frequency content without effecting the main resonant amplitude.

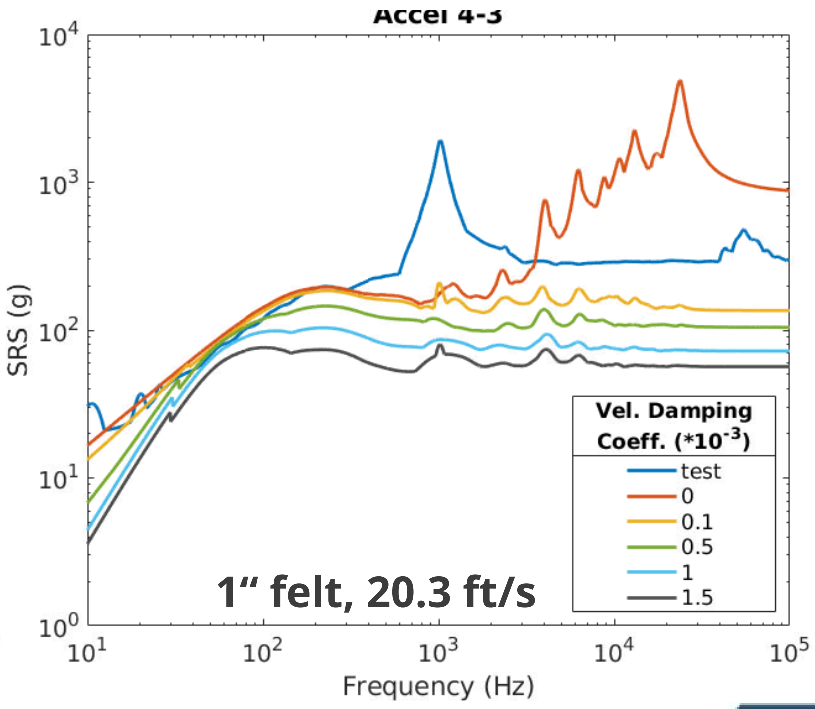
Hopkinson Bar Validation



Bare Resonant Plate



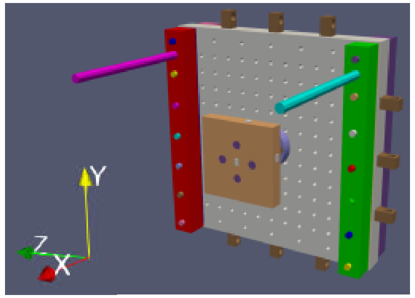




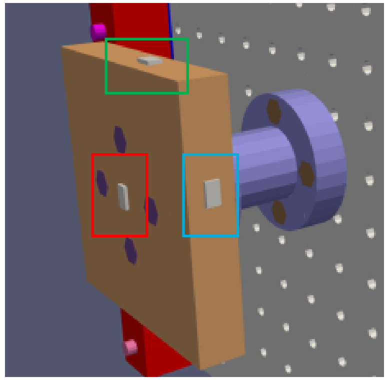
Results Comparison: Plate with Damping Bars and Component

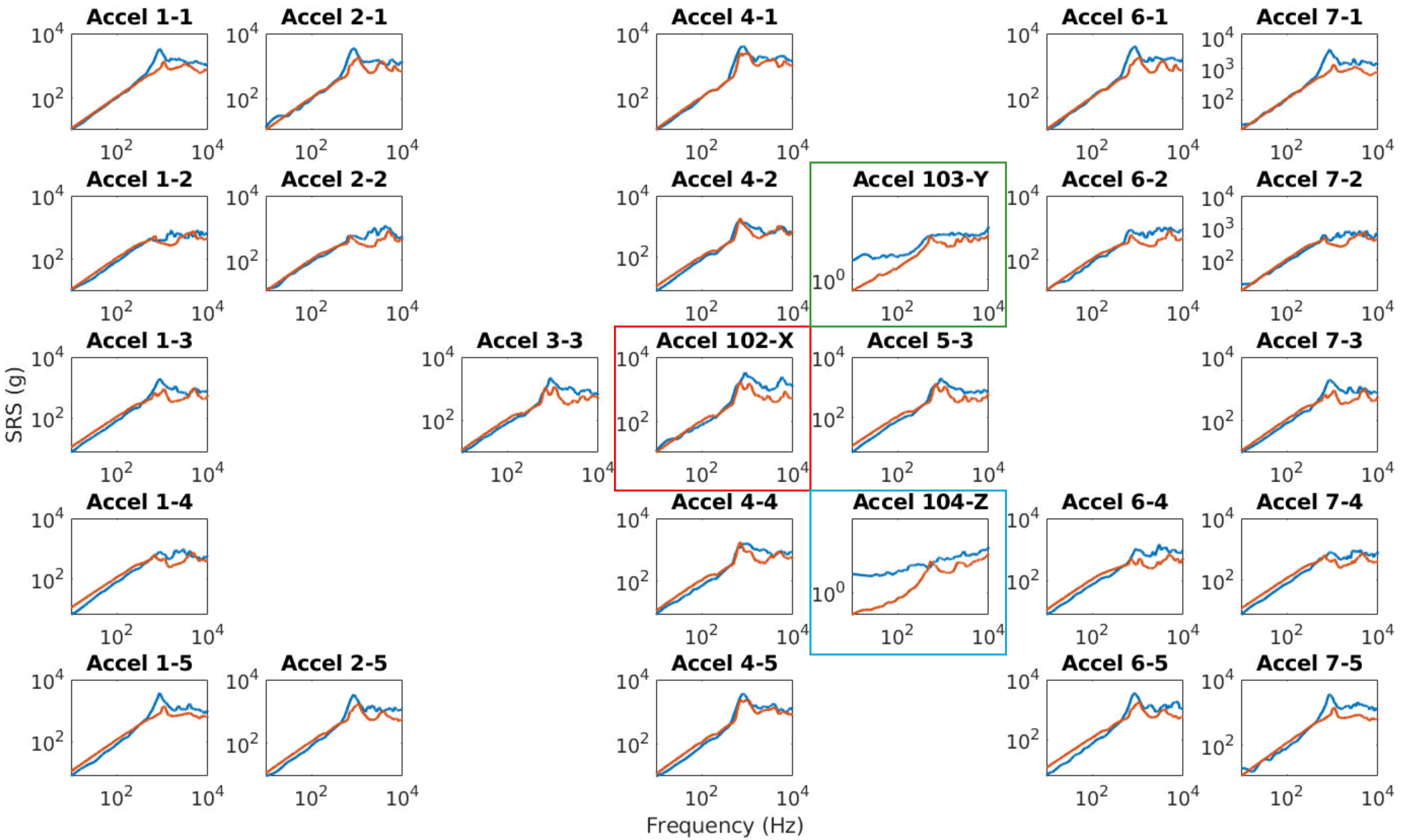
Test configuration:

- Plate with damping and component
- 12″ projectile
  - $v_i = 20.6$ ft/s
- 1/2″ felt



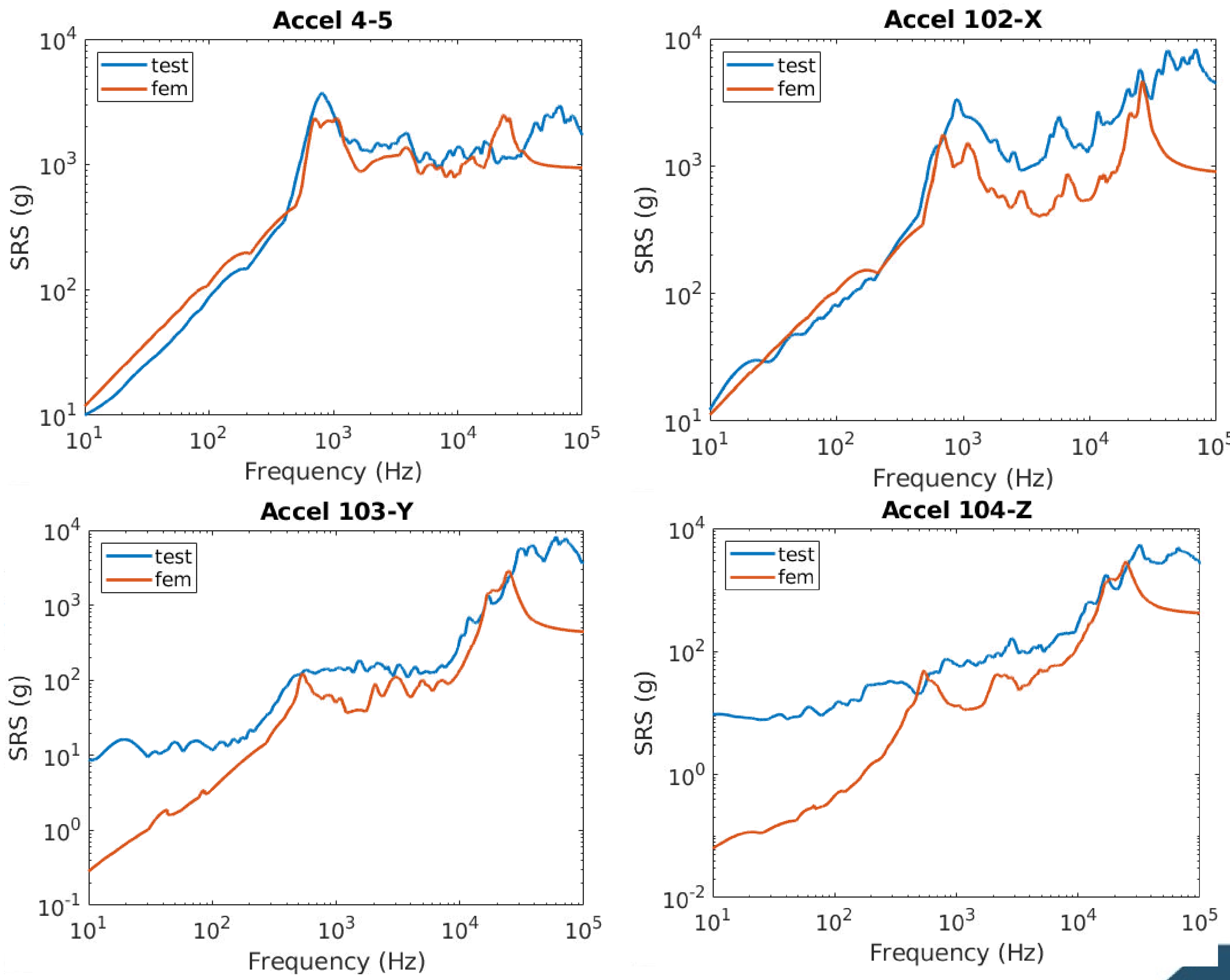
Accel 102, 103, 104 placement





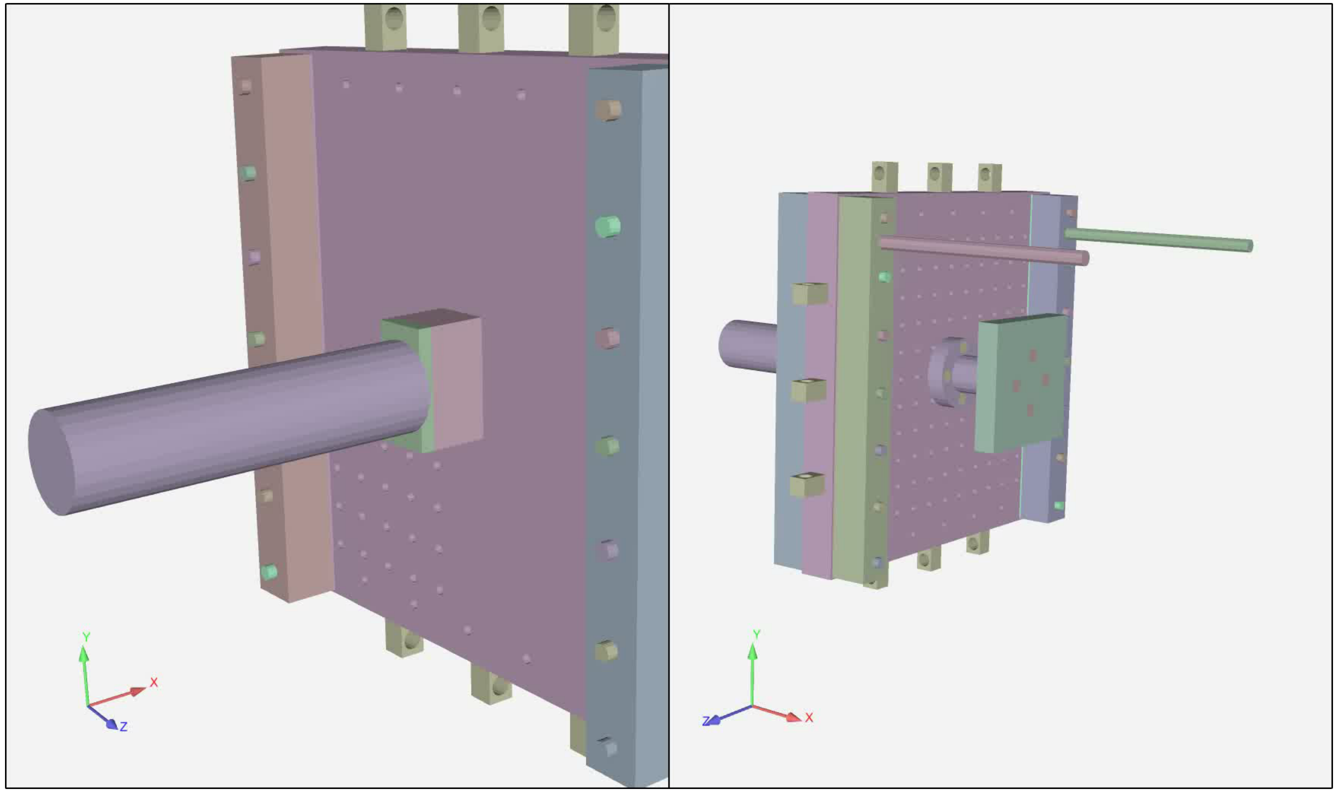
Results Comparison: Plate with Damping Bars and Component

- Accel 4-5 matches the test quite well. The first resonant peak is not sharp, but the general shape of the SRS is obtained through 10 kHz.
- Accel 102-X also matches the general shape of the test. The First resonant peak is split into two, and the amplitude is decreased between 1-10 kHz.
- Accel 103-Y and 104-Z have a small response at low frequencies.



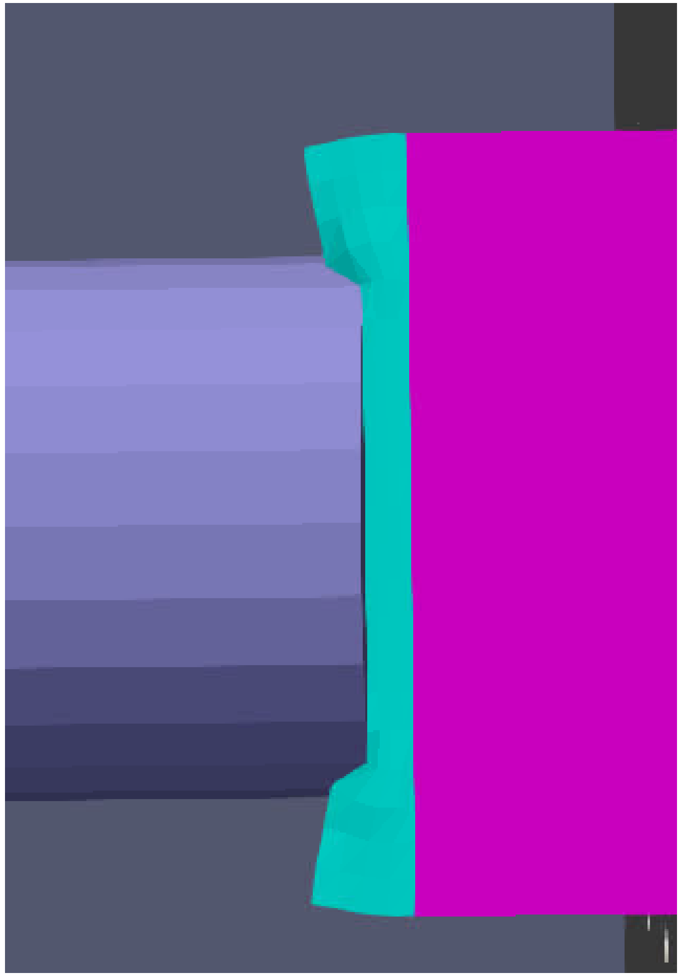
Conclusions

- A nonlinear model incorporating contact and friction, nonlinear materials, large deformations, and explicit dynamics was developed and simulated in Sierra SM.
- The resonant plate without damping bars and the component under test nearly identically matched the SRS response of the test through 10 kHz.
- Introducing velocity damping to the material felt volume eliminates .



Future work

- Optimize the felt material model to eliminate need of velocity damping
- Include support ropes to assess the importance of the boundary conditions on the simulation.
- Investigate the preload of the bolts on the damping bars.
- Offset the projectile/impact location to assess three-axis response.
- Design and optimize a fixture to meet specifications for a three-axis shock test.



Acknowledgements

- Tyler Schoenherr
- David Soine
- Mike Neilsen
- Mechanical shock Lab at SNL
- Coauthors, colleagues, and reviewers

- Thank you for your attention! Are there any questions?

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