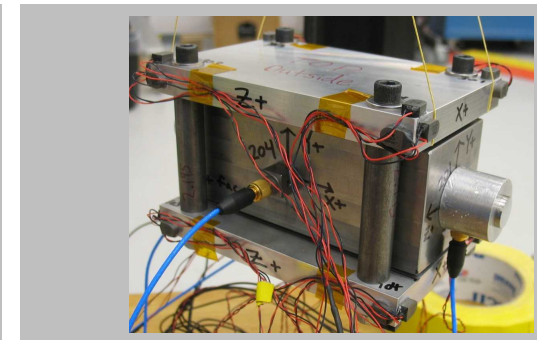
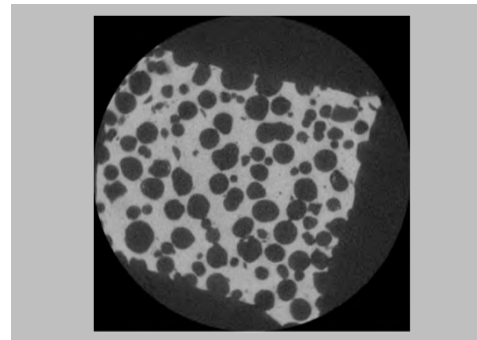
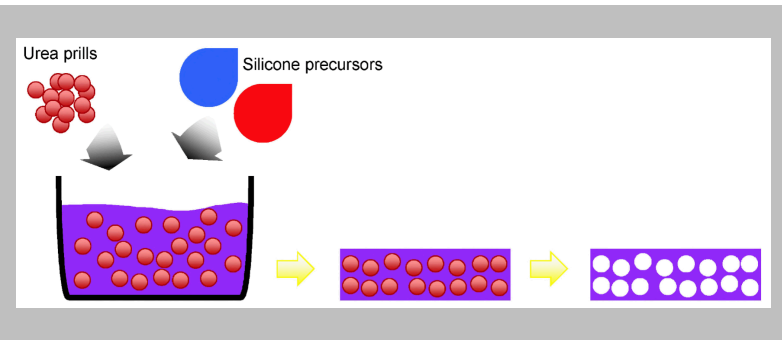


Empirically-Derived, Constitutive Damping Model for Cellular Silicone

1553



# Empirically-Derived, Constitutive Damping Model for Cellular Silicone

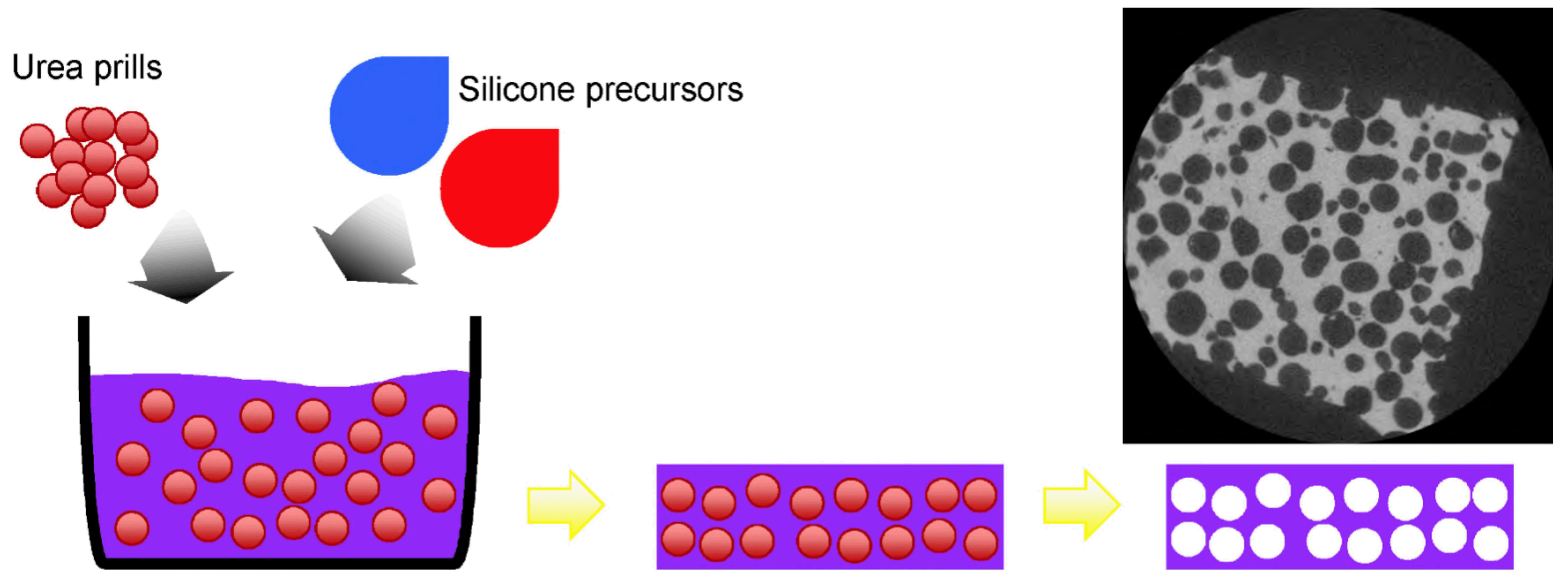
J. Russ (Org. 1553), B. Pacini (Org. 1522)

# Overview

- Background
- Experimental Processes
  - Test Fixture Design
  - Experimental Testing
  - Nonlinear Damping Extraction
- Analytical Processes
  - Linear Finite Element Model (FEM) Development
  - Constitutive Damping Model Derivation
  - Incorporation into the Linear FEM & Numerical Results
- Plans for Future Work

# Background

- Cellular silicone pads are frequently used for vibration / mechanical shock isolation between components
- Manufacturing process results in a random void structure



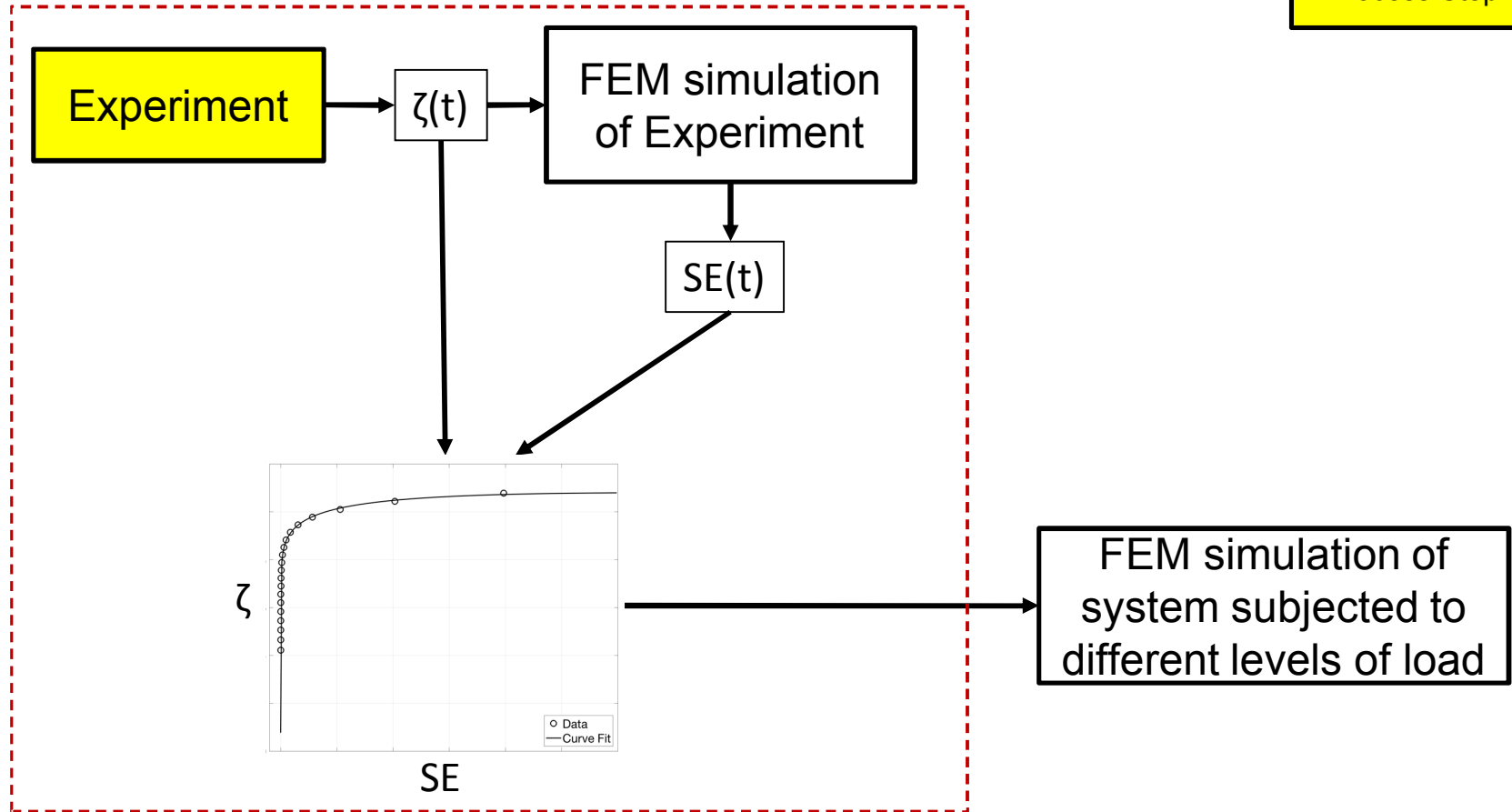
\* Illustration taken from Hammett, C. et al. "Modeling the Behavior of Cellular Silicone Pads in the Structure-Continuum Transition". SAND2014-4029C. Sandia National Laboratories, 2014.

# Process Roadmap

Format Legend

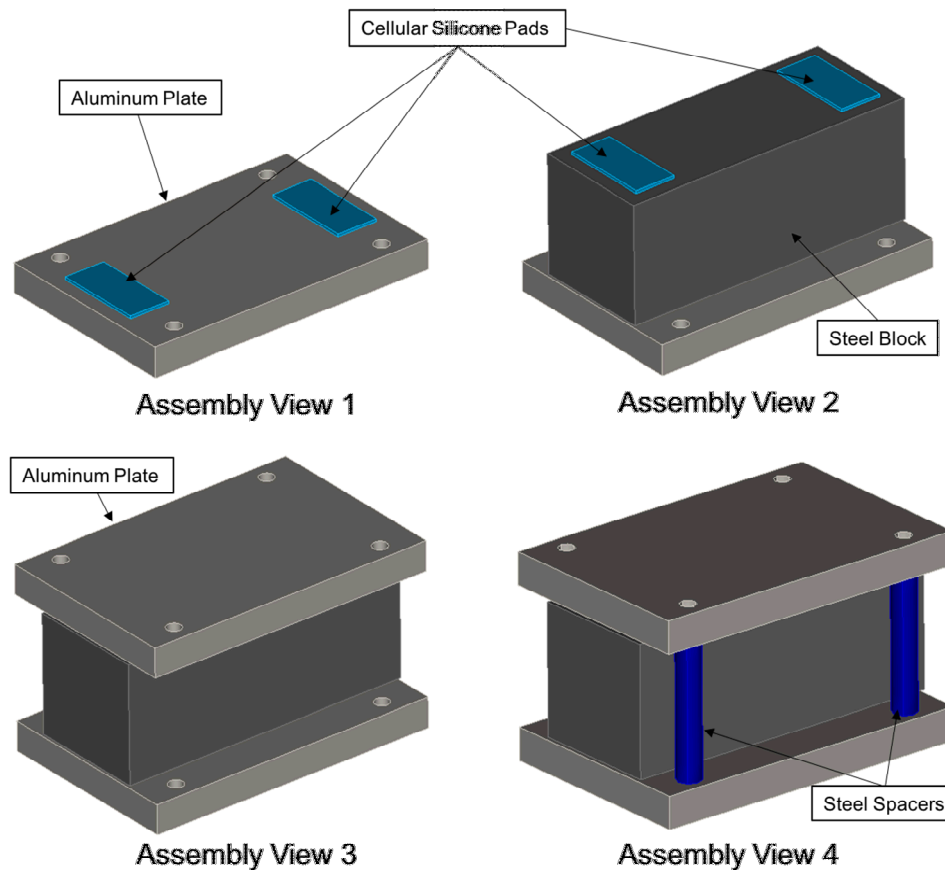
Current  
Process Step

## Development of Damping Model



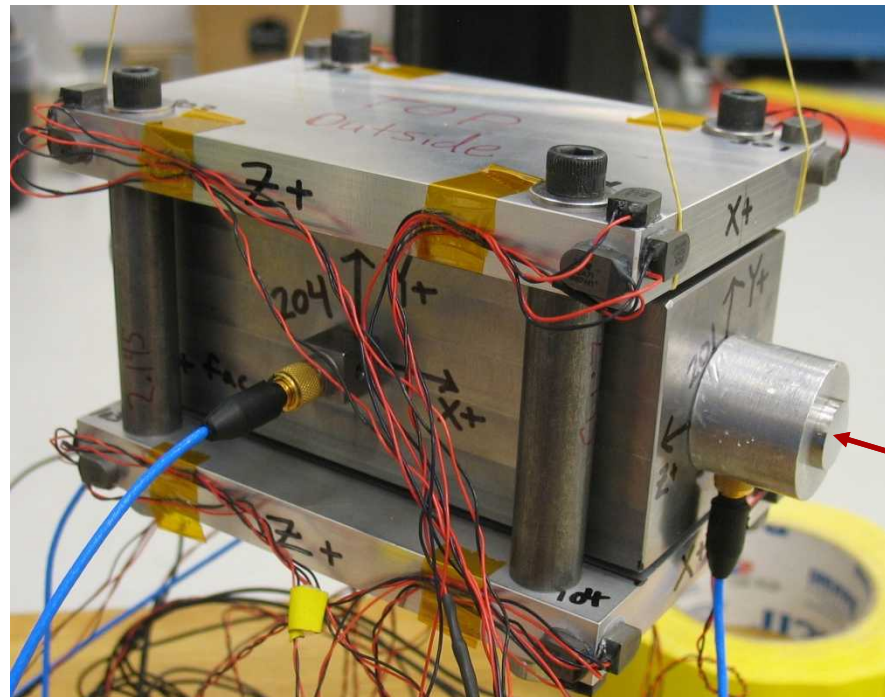
# Test Fixture Design

- Ensures strain energy develops only in the cellular silicone pads for the first 6 elastic modes of the system



# Experimental Testing

- Suspended with elastic bands to approximate a free-free boundary condition
- Two sets of impact modal tests
  - Low level excitation forces to extract linear properties
  - High level excitation forces to exercise the nonlinearities



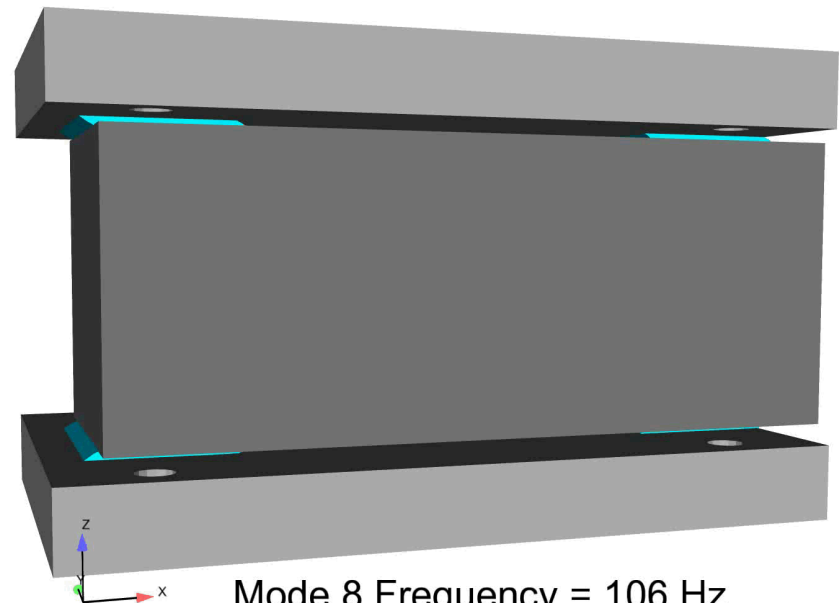
Hammer impact on aluminum cap to exercise nonlinearities

# Experimental Testing Continued

- Low level excitation forces for linear parameter extraction
  - Modes 7 - 10 involve primarily shear deformation of the cellular silicone and correspond to linear damping estimates of 6%cr
  - Modes 11 & 12 involve primarily tensile/compressive deformation and correspond to linear damping estimates of 10-12%cr

Mode	Frequency (Hz)	Damping (%cr)
7	93	6.37
8	106	5.98
9	116	6.24
10	127	6.12
11	190	11.91
12	209	10.28

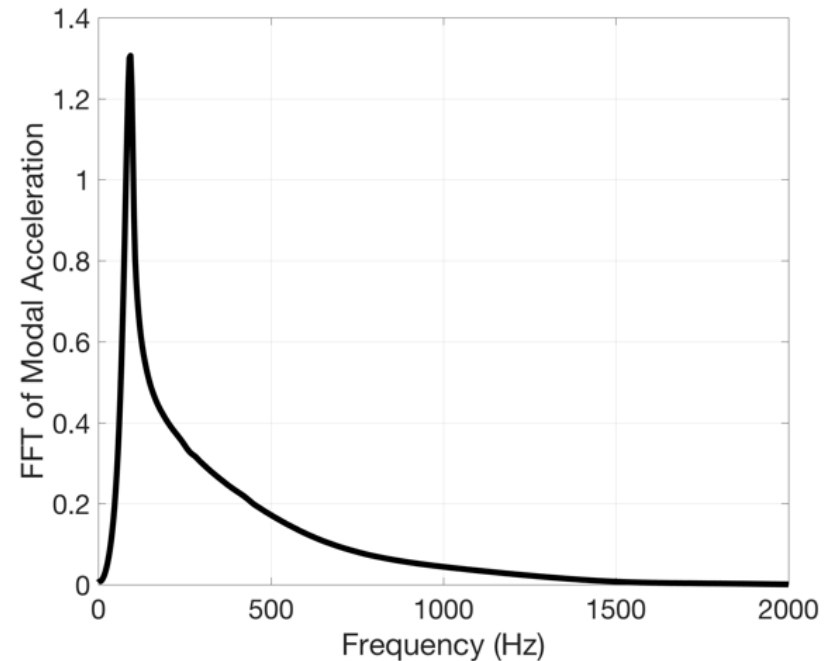
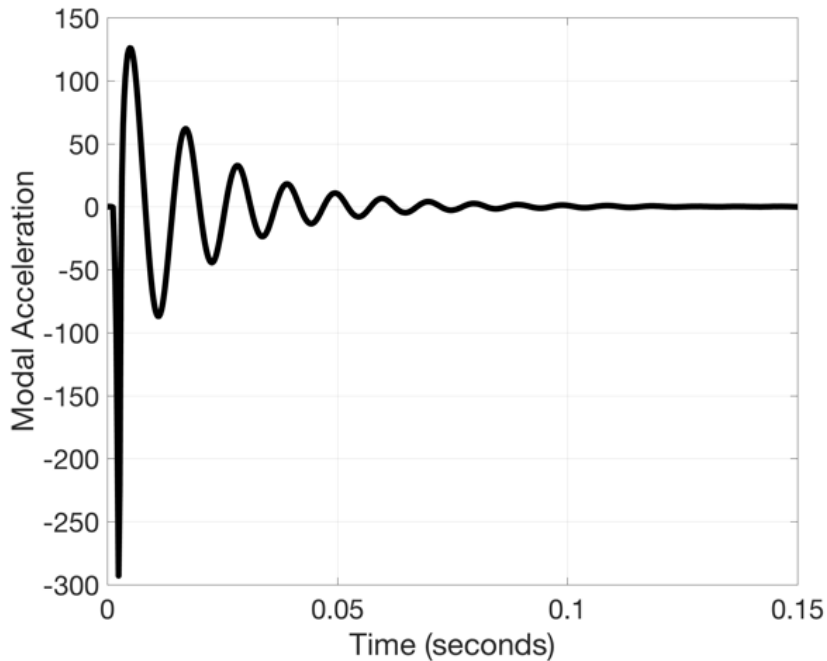
\*Six rigid body modes not shown



\* Bolts / spacers not shown for clarity \*

# Experimental Testing Continued

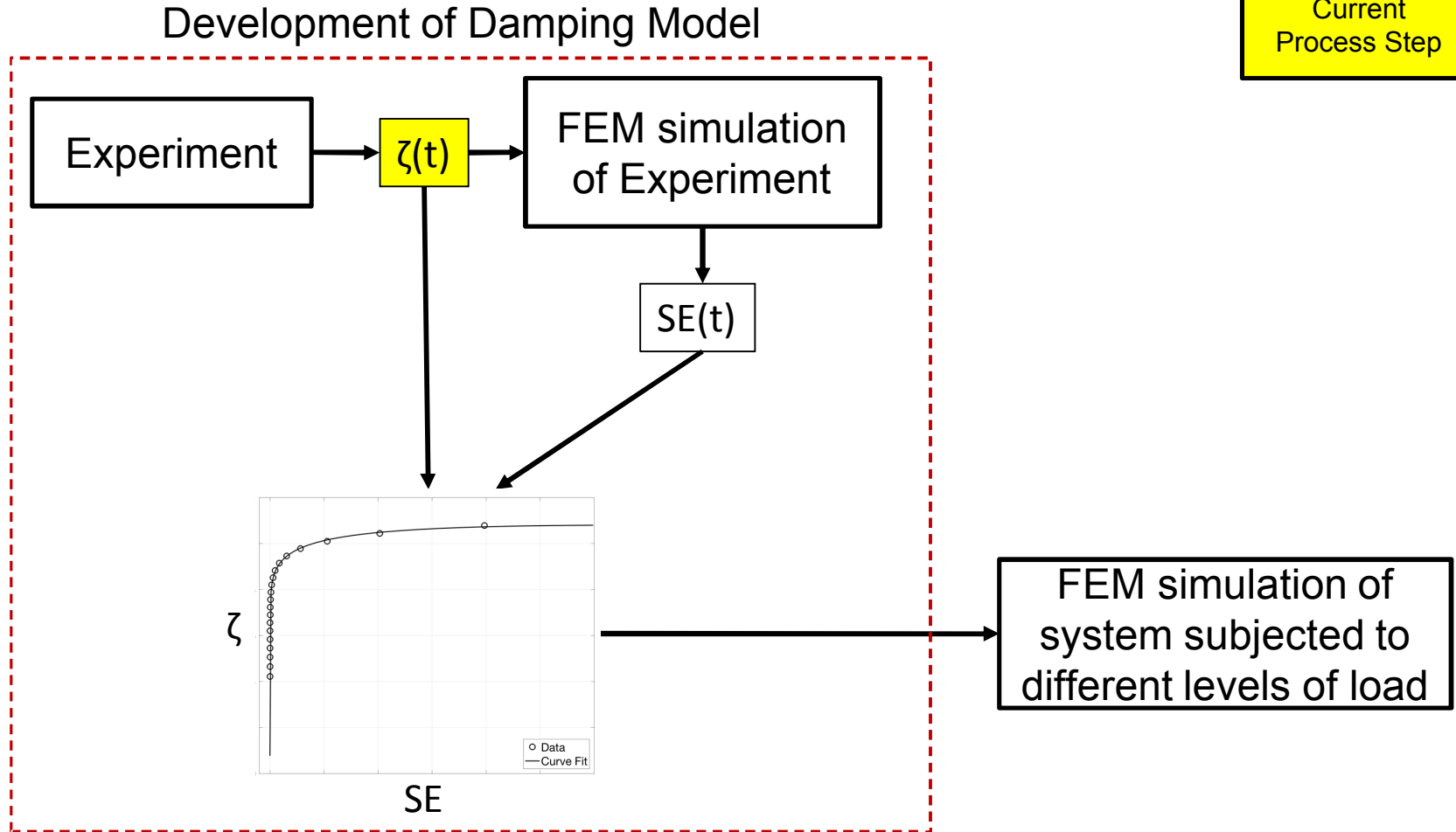
- High level excitation forces for nonlinear parameter extraction
  - Mode 8 selected for nonlinear analysis since it consists of primarily shear deformation and is directly excited by hammer input
- Modal filter applied to isolate the response of Mode 8 when the steel block was subjected to a 44, 178, and 311 N hammer impact. (Figures below correspond to Mode 8 response to 311 N impact)



# Process Roadmap

Format Legend

Current Process Step

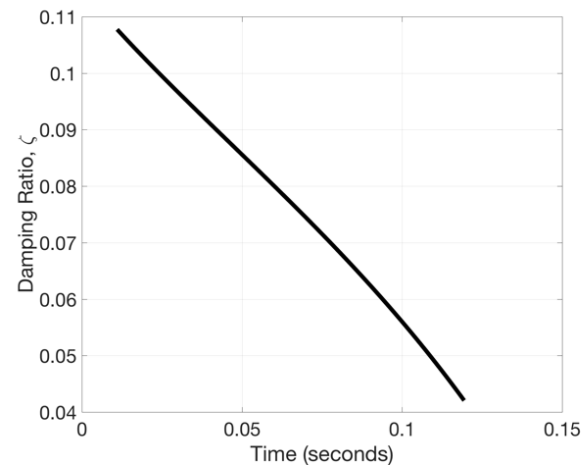
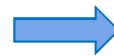


# Nonlinear Damping Extraction

Fit modal acceleration of Mode 8 to functional form:  $\ddot{q}(t) = e^{d(t)} \cos[\theta(t)]$

- Step 1: Compute the analytic signal,  $\ddot{Q}(t) = \ddot{q}(t) + i \mathcal{H}[\ddot{q}(t)]$ , where  $\mathcal{H}[\ddot{q}(t)]$  represents the Hilbert transform of the modal acceleration
- Step 2: Fit a cubic polynomial to both the decay,  $d(t)$ , and the phase,  $\theta(t)$   
 $d(t) = \ln|\ddot{Q}(t)|$  and  $\theta(t) = \arg[\ddot{Q}(t)]$
- Step 3: Compute the time varying damped and undamped natural frequency  
 $\omega_d(t) \triangleq \dot{\theta}(t)$  and  $\omega_n(t) \triangleq (\omega_d(t)^2 + \dot{d}(t)^2)^{\frac{1}{2}}$
- Step 4: Compute the time varying damping ratio,  $\zeta(t) \triangleq \frac{\dot{d}(t)}{\omega_n(t)}$

Computed damping ratio as a function of time for Mode 8. This curve will be implemented into the FEM to develop constitutive damping model as a function of strain energy.

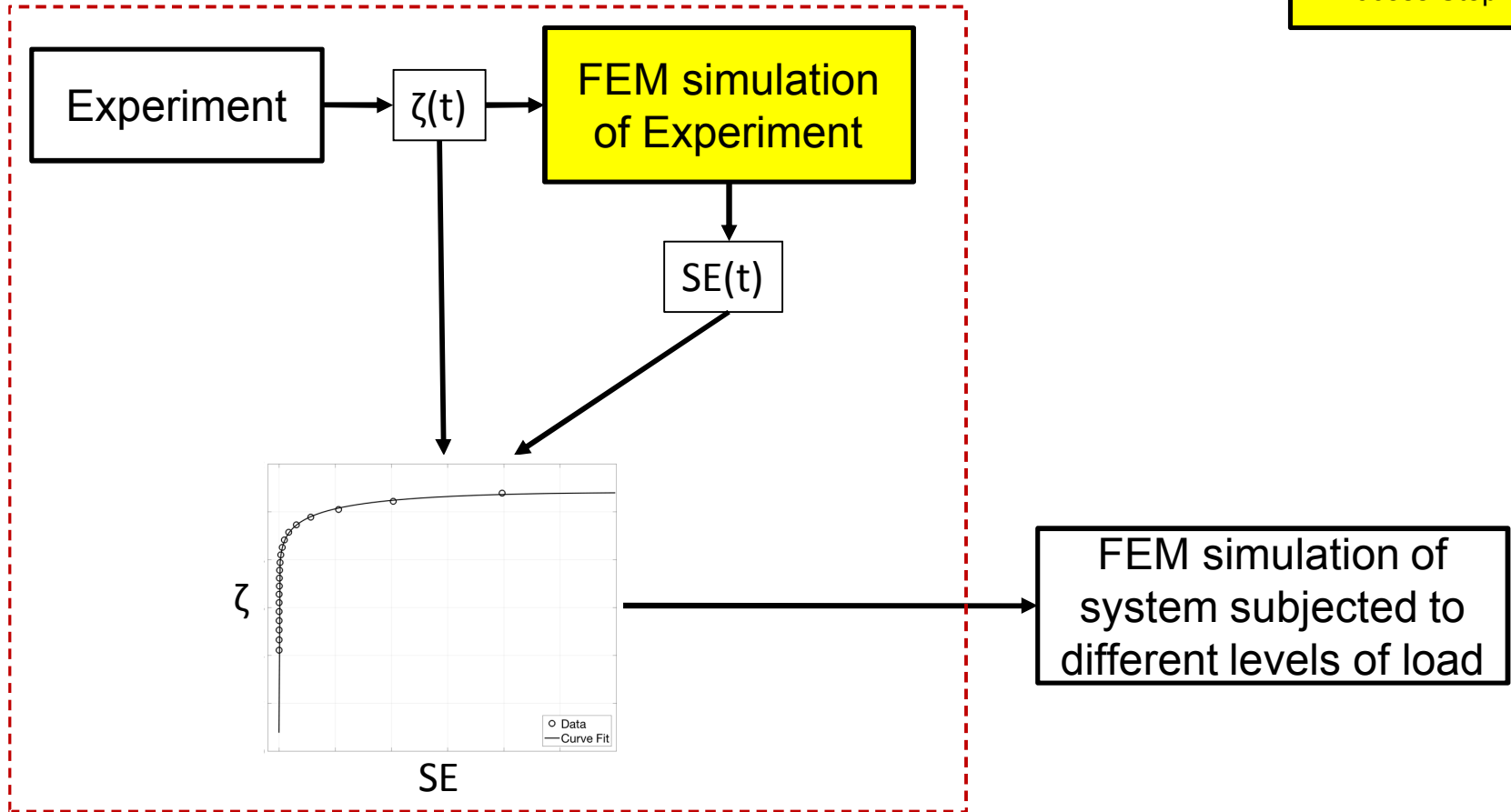


# Process Roadmap

Format Legend

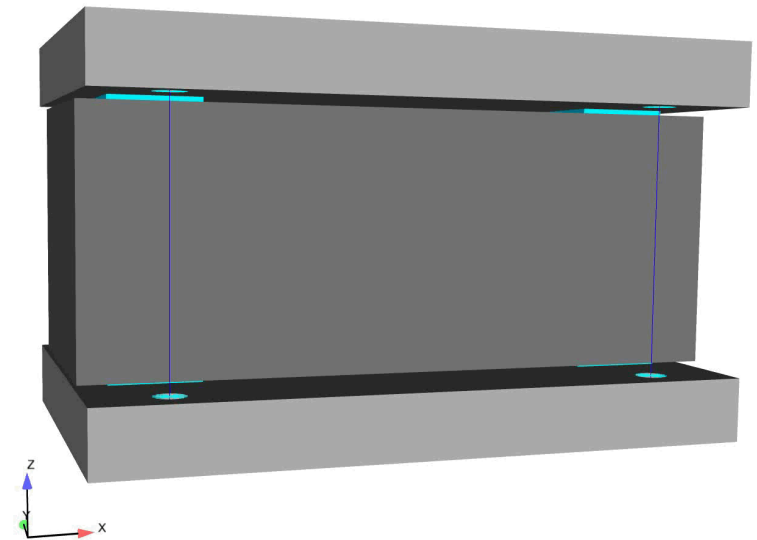
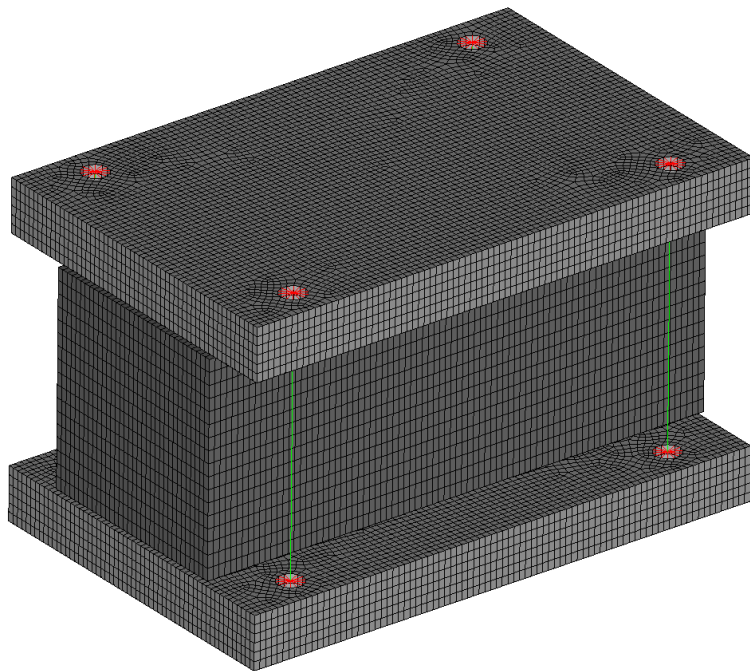
Current  
Process Step

## Development of Damping Model



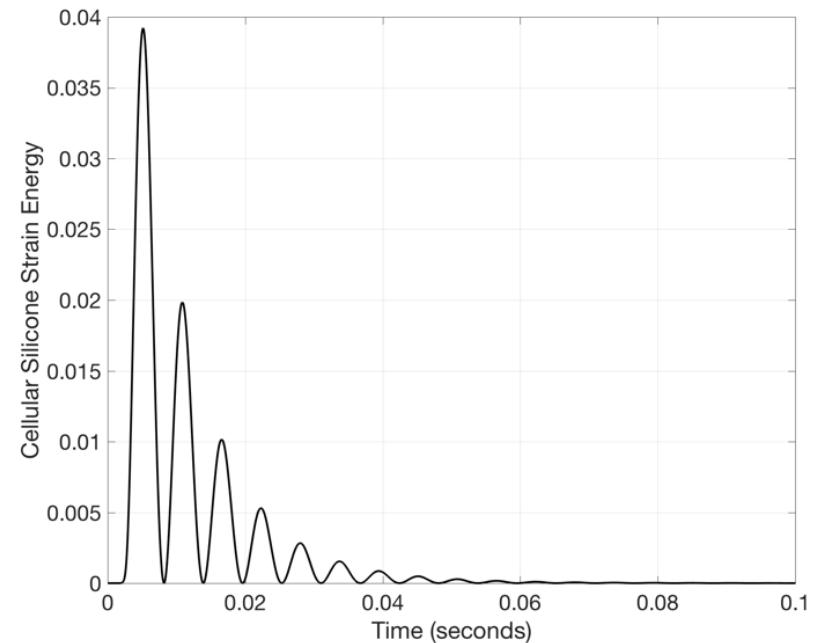
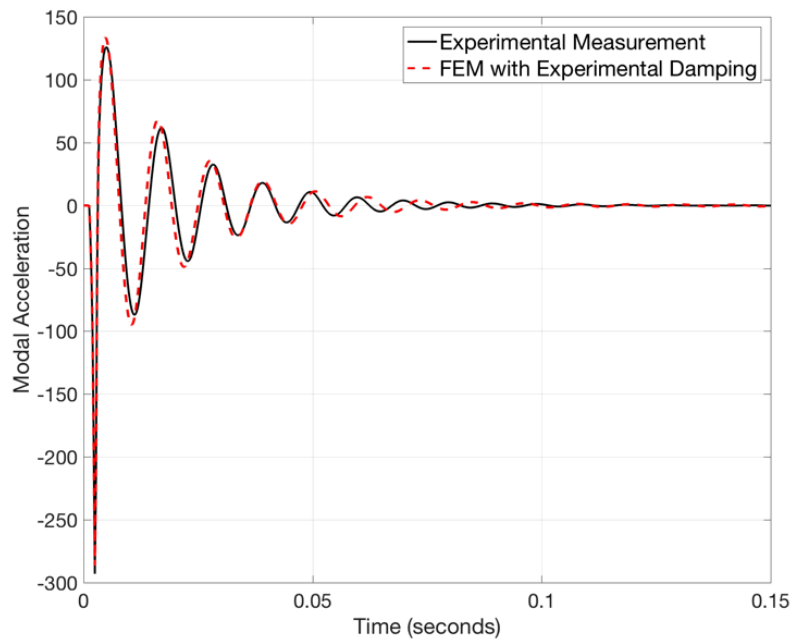
# Linear Finite Element Model Development

- Sierra SD (Structural Dynamics) was used to compute the system modal frequencies and mode shapes
- Cellular silicone material modeled as a linear elastic, isotropic material with an elastic modulus and Poisson's ratio found via calibration to modal test data



# Constitutive Damping Model Derivation Continued

- Mode 8 analytical response computed using...
  - Damping ratio versus time curve extracted from experiment
  - Decreased cellular silicone elastic modulus in order to account for the stiffness nonlinearity
  - Computed modal force from the 311 N hammer impact
$$\ddot{q}_8(t) + 2 \cdot \zeta_8(t) \cdot \omega_8 \cdot \dot{q}_8(t) + \omega_8^2 q_8(t) = \underline{\varphi}_8^T \underline{F}(x, t)$$
- FEM used to compute the strain energy in the cellular silicone

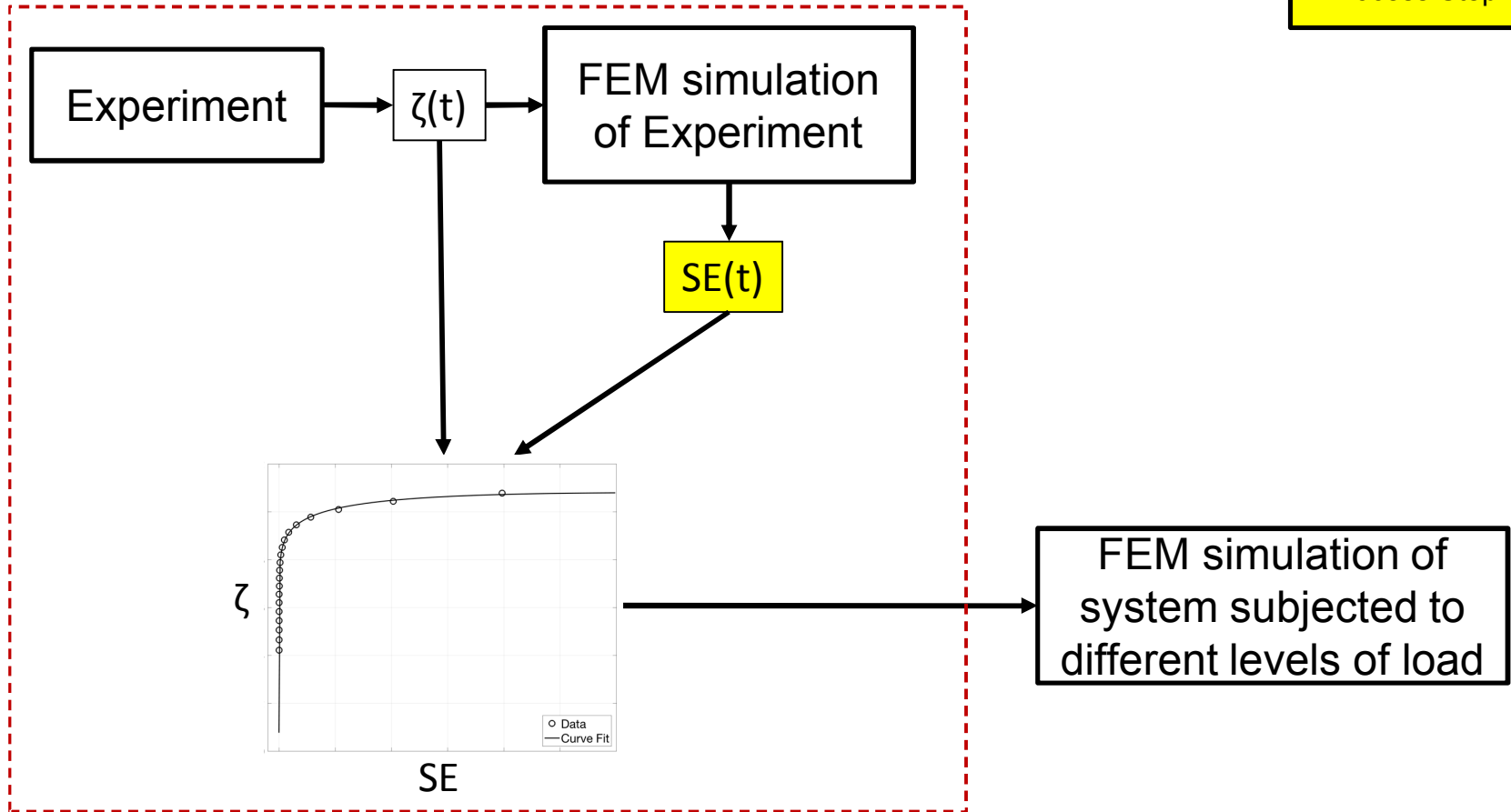


# Process Roadmap

Format Legend

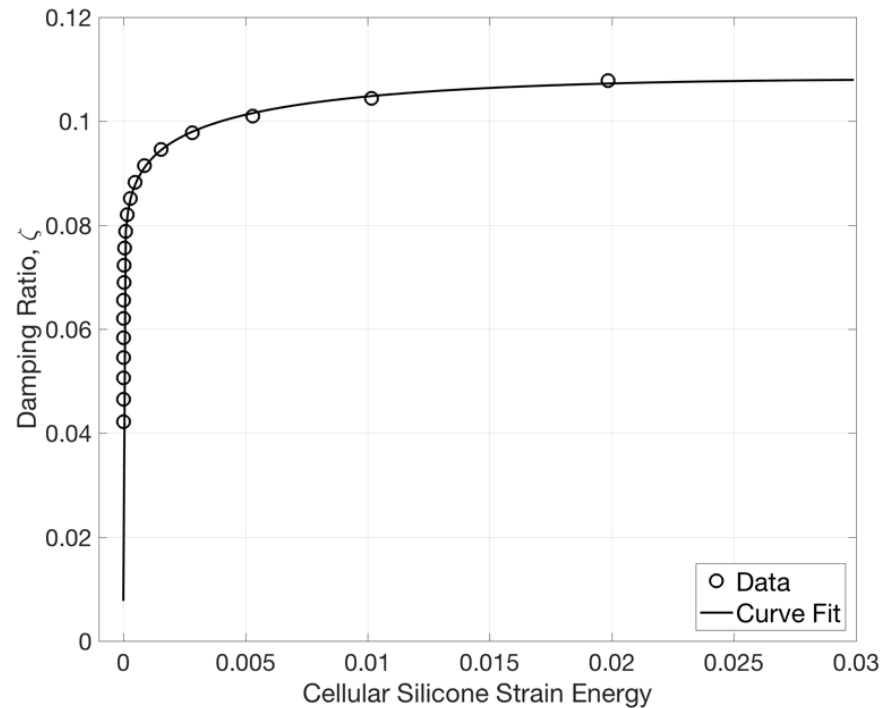
Current  
Process Step

## Development of Damping Model



# Constitutive Damping Model Derivation Continued

- Create a curve fit of the measured damping ratio for Mode 8 versus the *peaks* in the strain energy
  - Fourth order polynomial fit to the logarithm of the data



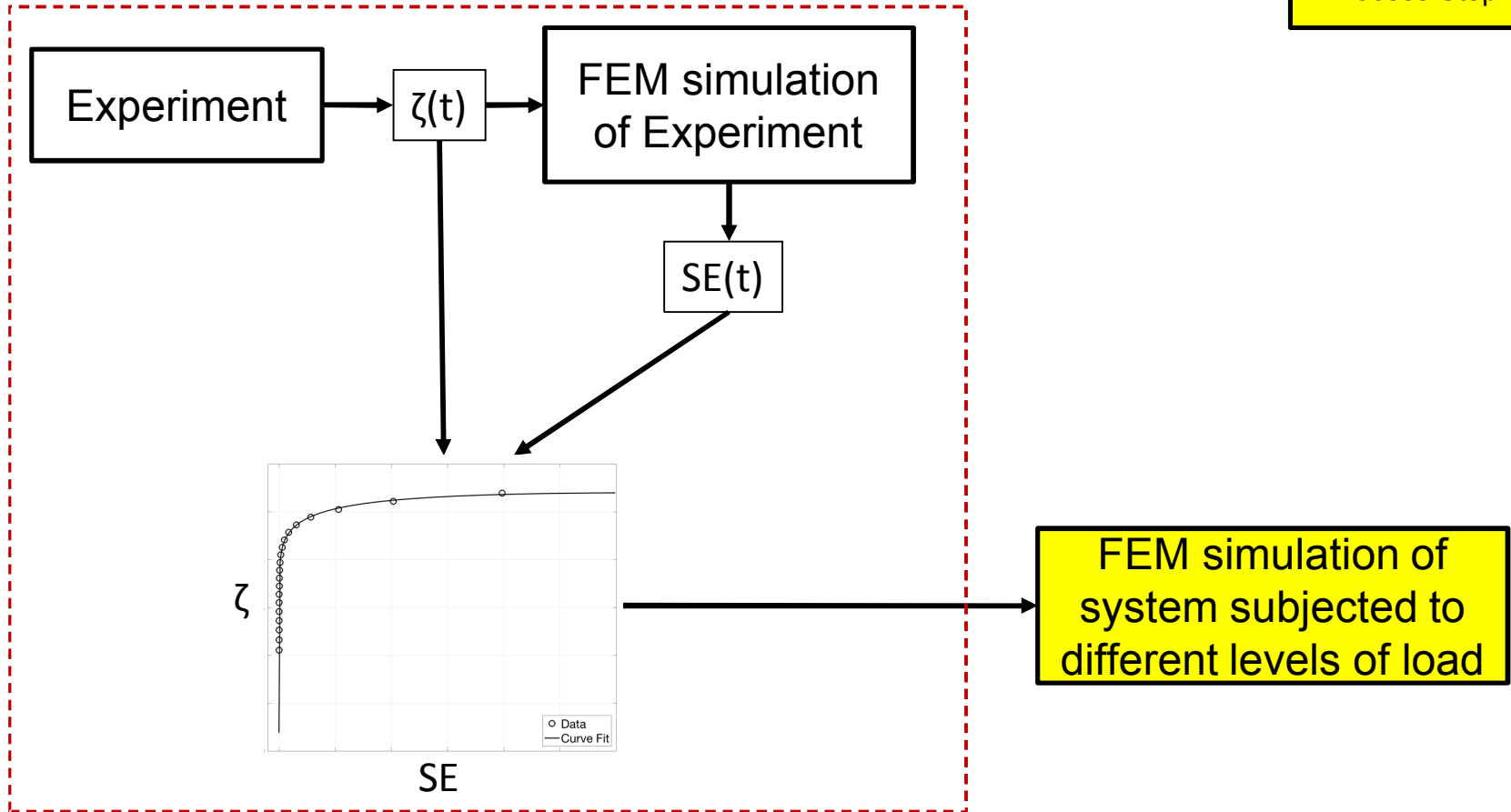
$$\log_{10}(\zeta(SE_{CS})) = -0.0034 \cdot \log_{10}(SE_{CS})^4 - 0.042 \cdot \log_{10}(SE_{CS})^3 - 0.196 \cdot \log_{10}(SE_{CS})^2 - 0.345 \cdot \log_{10}(SE_{CS})^1 - 1.168$$

# Process Roadmap

Format Legend

Current  
Process Step

## Development of Damping Model

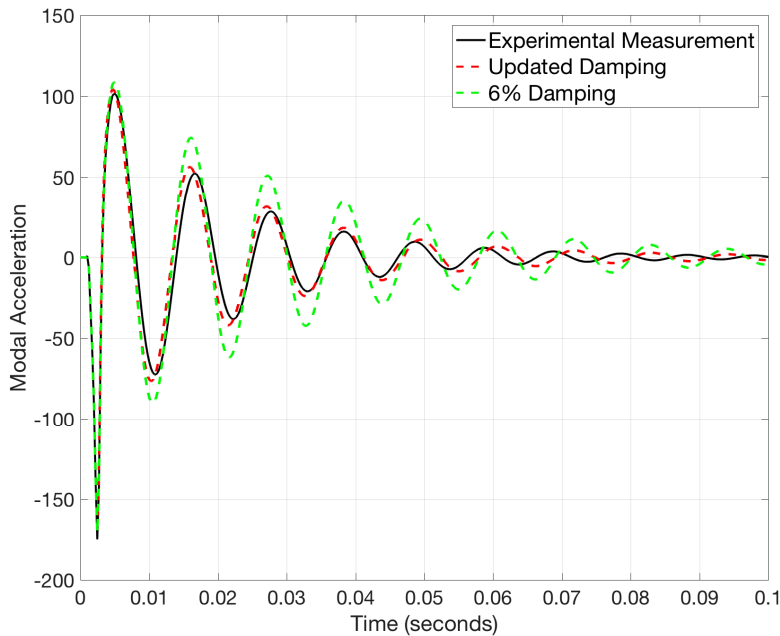


# Incorporation into the Linear FEM

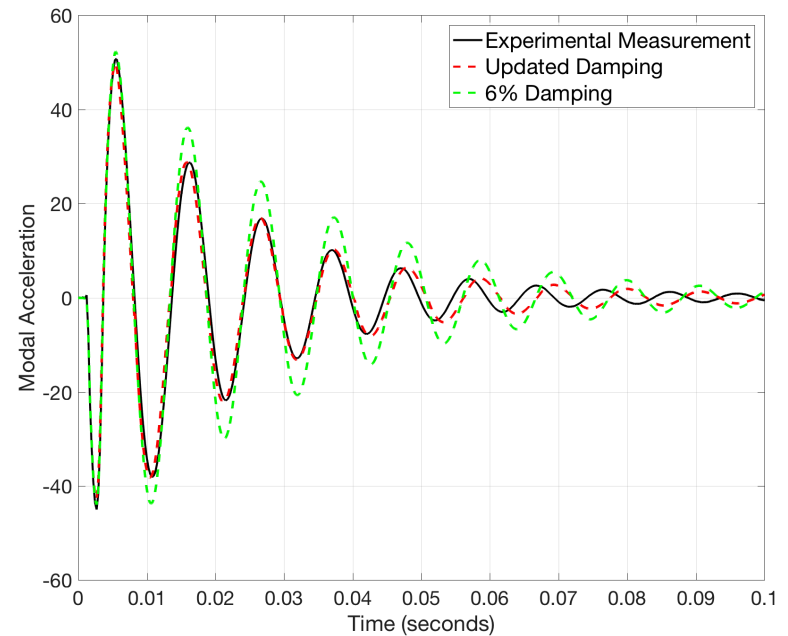
- Analytically compute the modal response of Mode 8 when subjected to the 44 and 178 N hammer impacts

$$\ddot{q}_8(t) + 2 \cdot \zeta_8(SE_{CS}) \cdot \omega_8 \cdot \dot{q}_8(t) + \omega_8^2 q_8(t) = \underline{\varphi}_8^T \underline{F}(x, t)$$

where  $SE_{CS}$  is the current strain energy in the cellular silicone pads



Response to 178 N Impact



Response to 44 N Impact

# Conclusions / Plans for Future Work

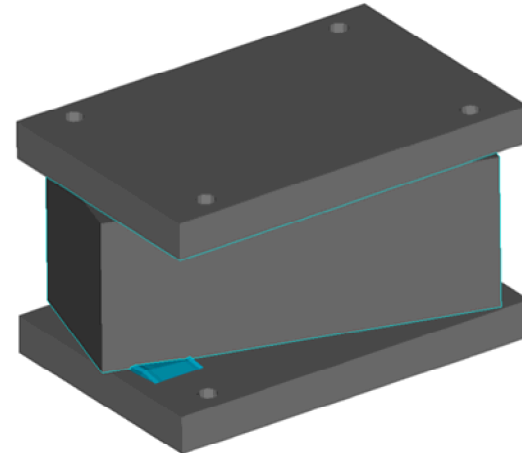
- Results are promising for the same system subjected to two different load levels
- Change the system being tested and the applied load to determine whether this approach to applying modal damping improves predictive accuracy in a more general setting
- Derive a similar model for tensile/compressive deformation modes of the cellular silicone

# BACK-UP SLIDES

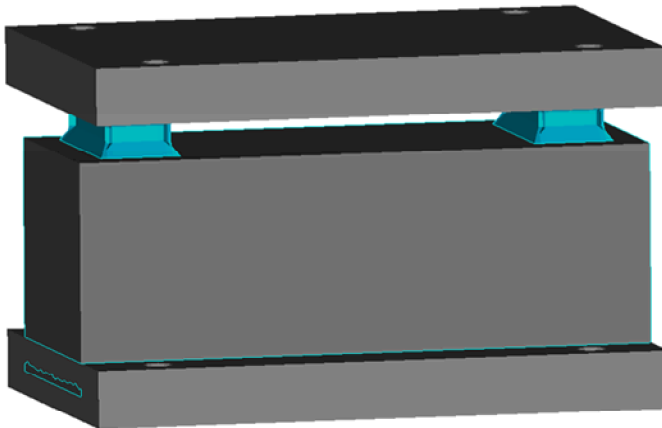
# Example System Mode Shapes



Mode 8 Frequency = 106 Hz



Mode 9 Frequency = 116 Hz

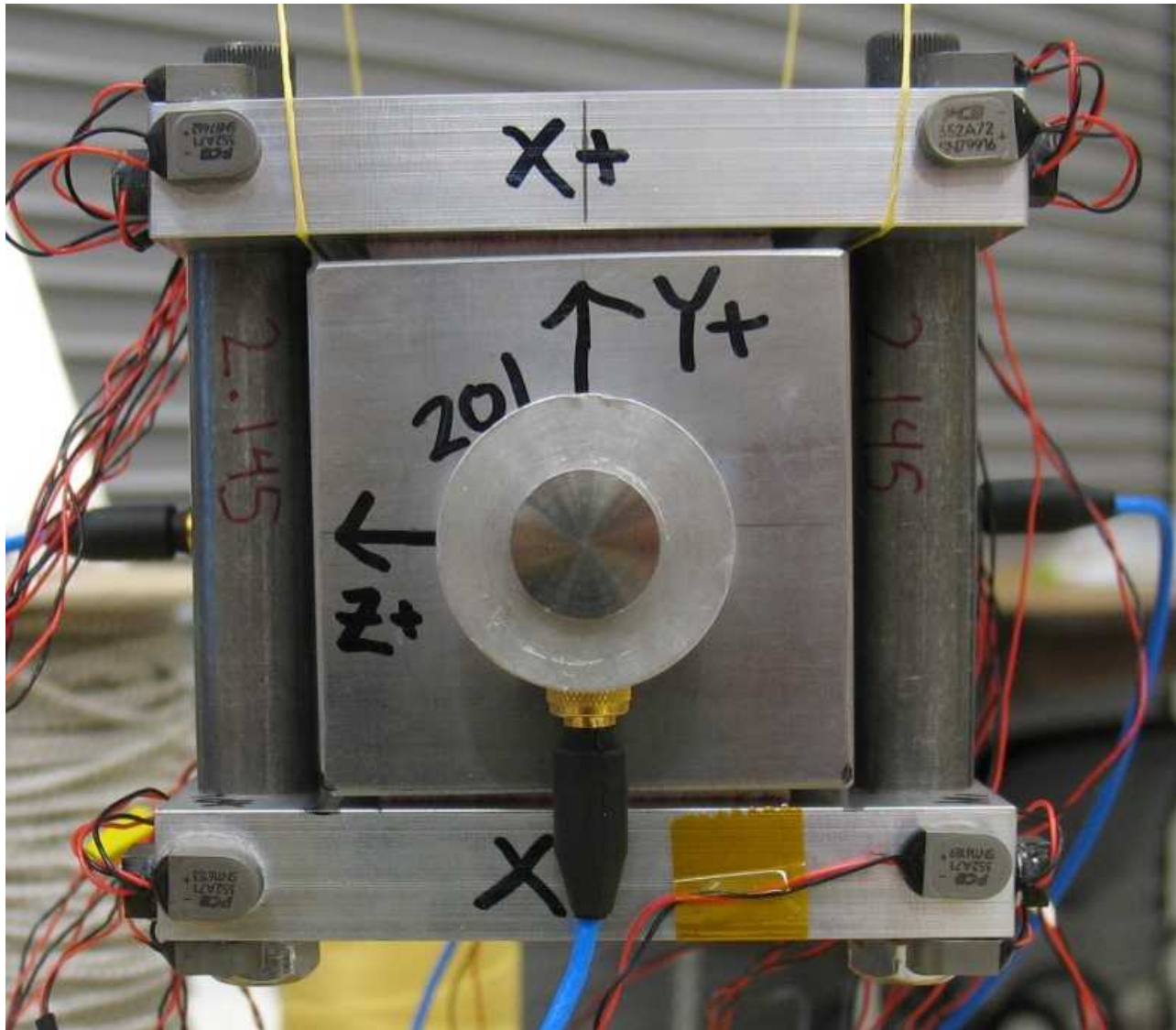


Mode 11 Frequency = 190 Hz

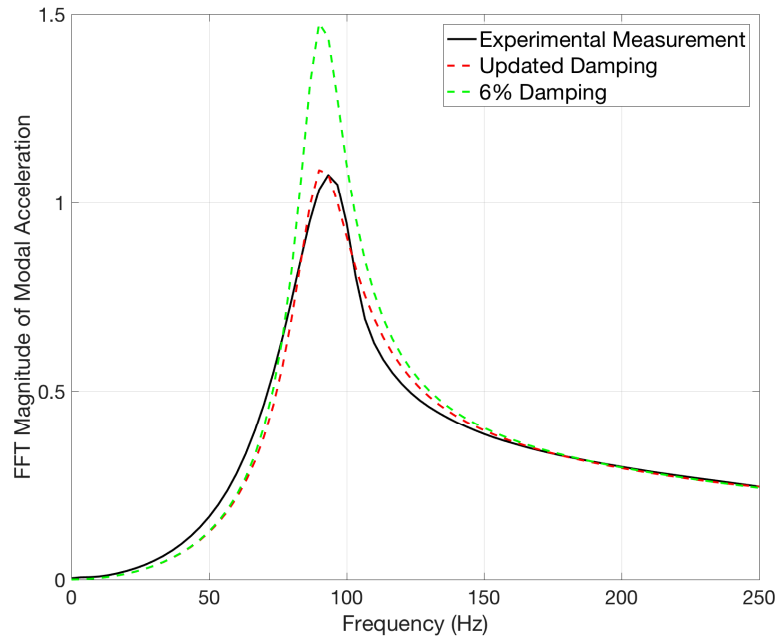


Mode 12 Frequency = 209 Hz

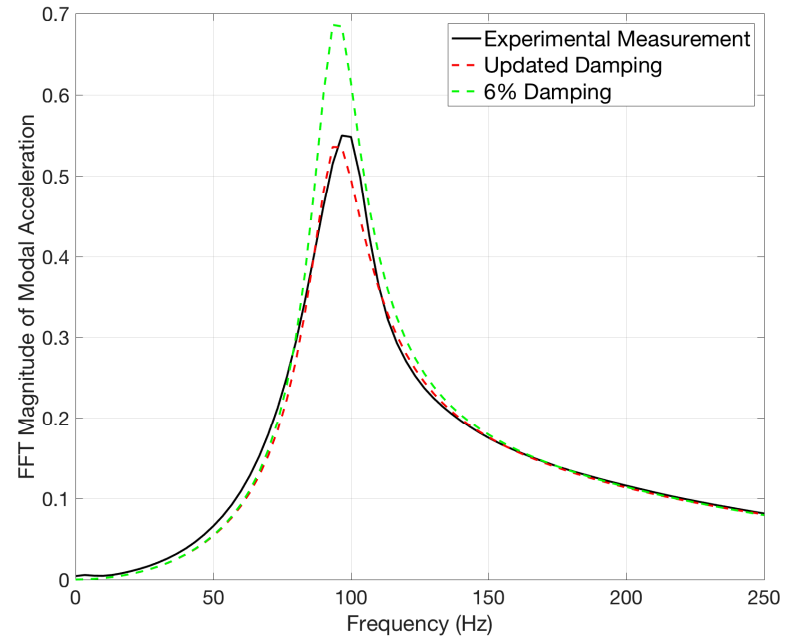
# Additional Fixture Photo



# Frequency Domain Responses



Response to 178 N Impact



Response to 44 N Impact