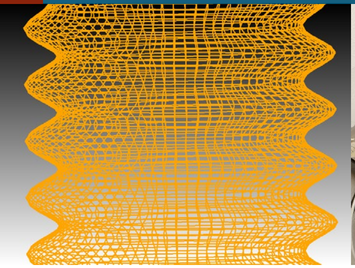
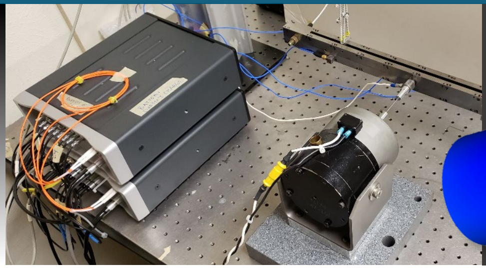
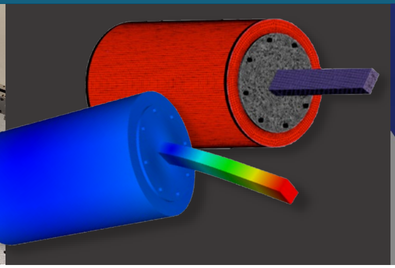
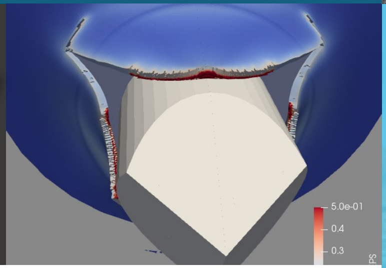
Model Validation of a Modular Foam Encapsulated Electronics Assembly With Controlled Preloads Via Additively Manufactured Silicone Lattices









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About Us

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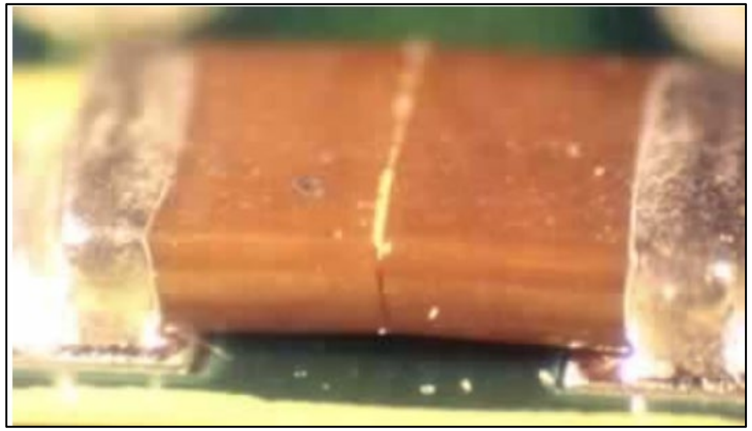
Presentation Overview

1. Project Motivation
2. Experimental Overview
3. Material and Finite Element Modeling Strategy
4. Solid Mechanics (SM) Simulations
5. Structural Dynamics (SD) Simulations
6. Results
7. Conclusions and Future Work

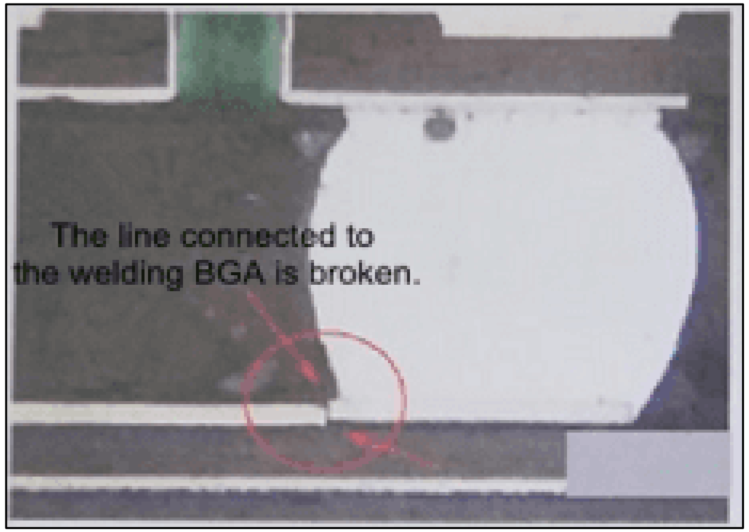
Background – vibrations of electronic assemblies

- Electronic assemblies are vital to Sandia's nuclear deterrence mission and can be exposed to harsh mechanical environmental conditions.



Broken Capacitor from Flexure [1]

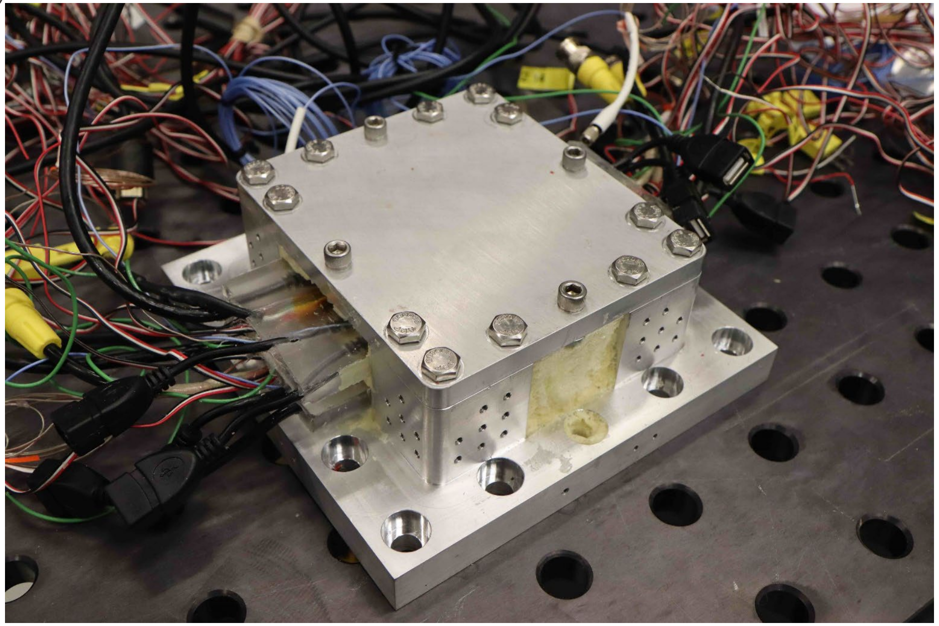
- Failures resulting from demanding static (assembly) and dynamic (vibration or shock) environments include:
  - Cracking of circuit board base
  - Discontinuity of soldered connections
  - Permanent failure of strain-sensitive components (ceramic capacitors, ball grid arrays, etc.)



Severed Trace due to Vibrations [2]

Introduction – Traditionally Potted Foam Encapsulation

- **Current paradigm:** encapsulation foams protect electronics from mechanical shock and vibration but they are not agile as currently deployed



- Functionality
  - Encapsulation foam inside components
  - Structural – Environment damping and mechanical support
  - Cavity-filling protection in radiation environments

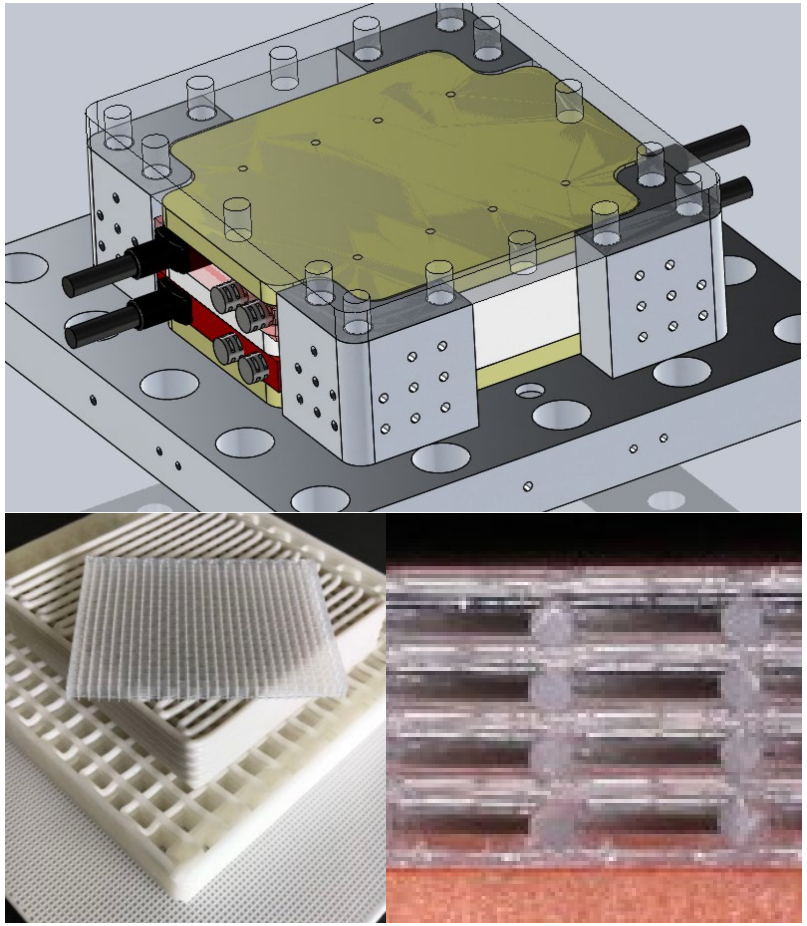
- Issues with traditional foam
  - Difficult surveillance of parts potted in foam
  - Lacking Agility for Future Systems
    - No part reuse
    - Requires redesign of potting process for new internal configurations

Introduction – Modular Foam Development

- **Need**: A new paradigm of electronics packaging that overcomes manufacturing, surveillance, and part replacement/reuse issues from the current paradigm

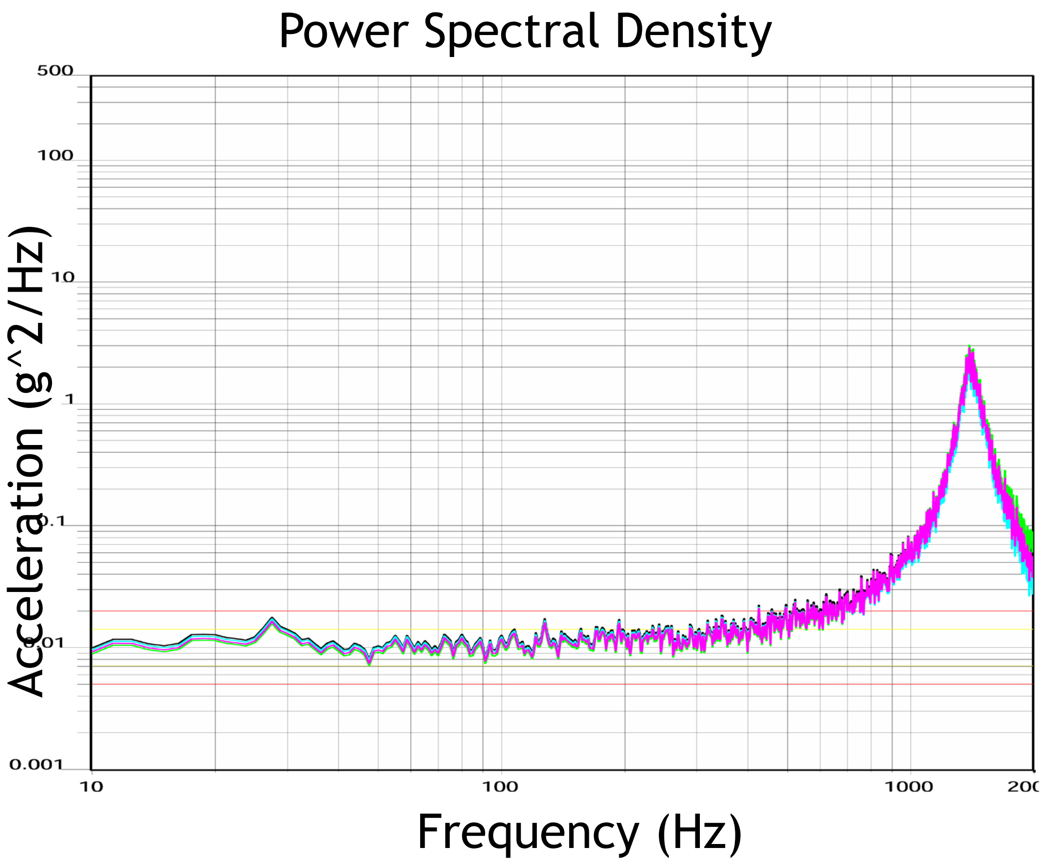
- **Approach**: Use physically compressed soft and rigid foams to protect the electronics by taking advantage of additive manufacturing to control the stiffness of the soft layers

- Application
  - **Protection of electronics** in environments
  - **Design of foams** relative of components and cable (surfaces, pass throughs, etc.)
  - **Pre-compression** of components and functionality
- Science and Engineering
  - **Materials selection** and **modeling**
  - **Friction**
  - **Pre-compression** level of foam

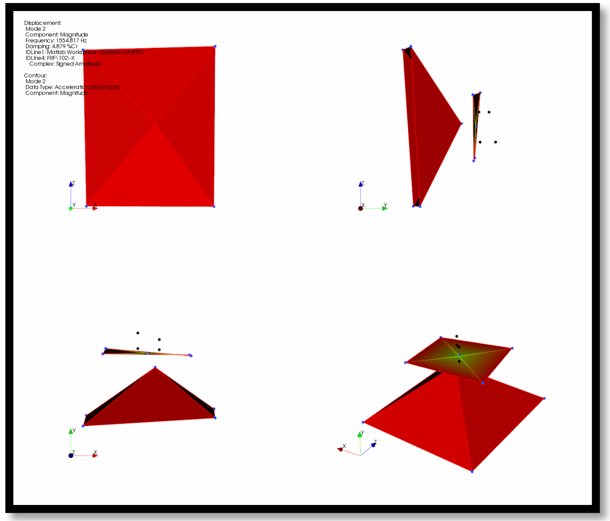


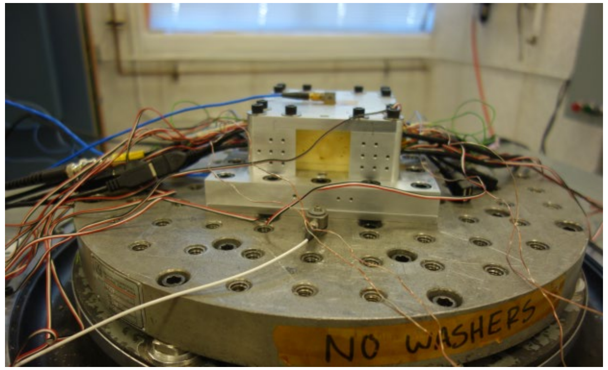
Experimental results

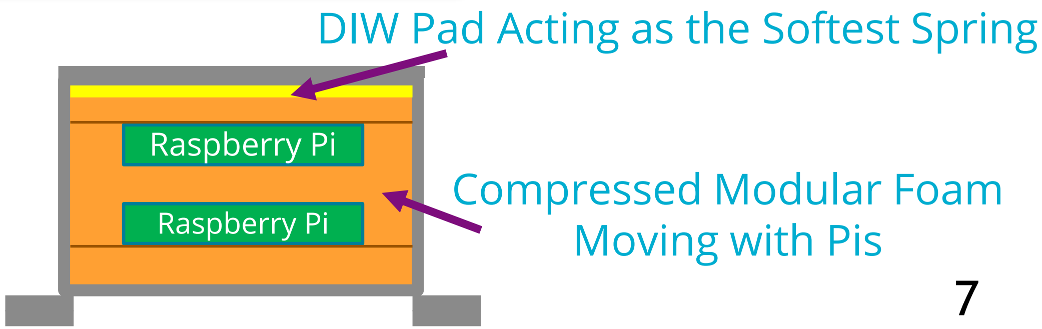
Power spectral density is determined from data gathered by accelerometers attached to assembly excited by shaker table



Example Shape from the Free-Floating Pi, Modular Foam Assembly Unit 1

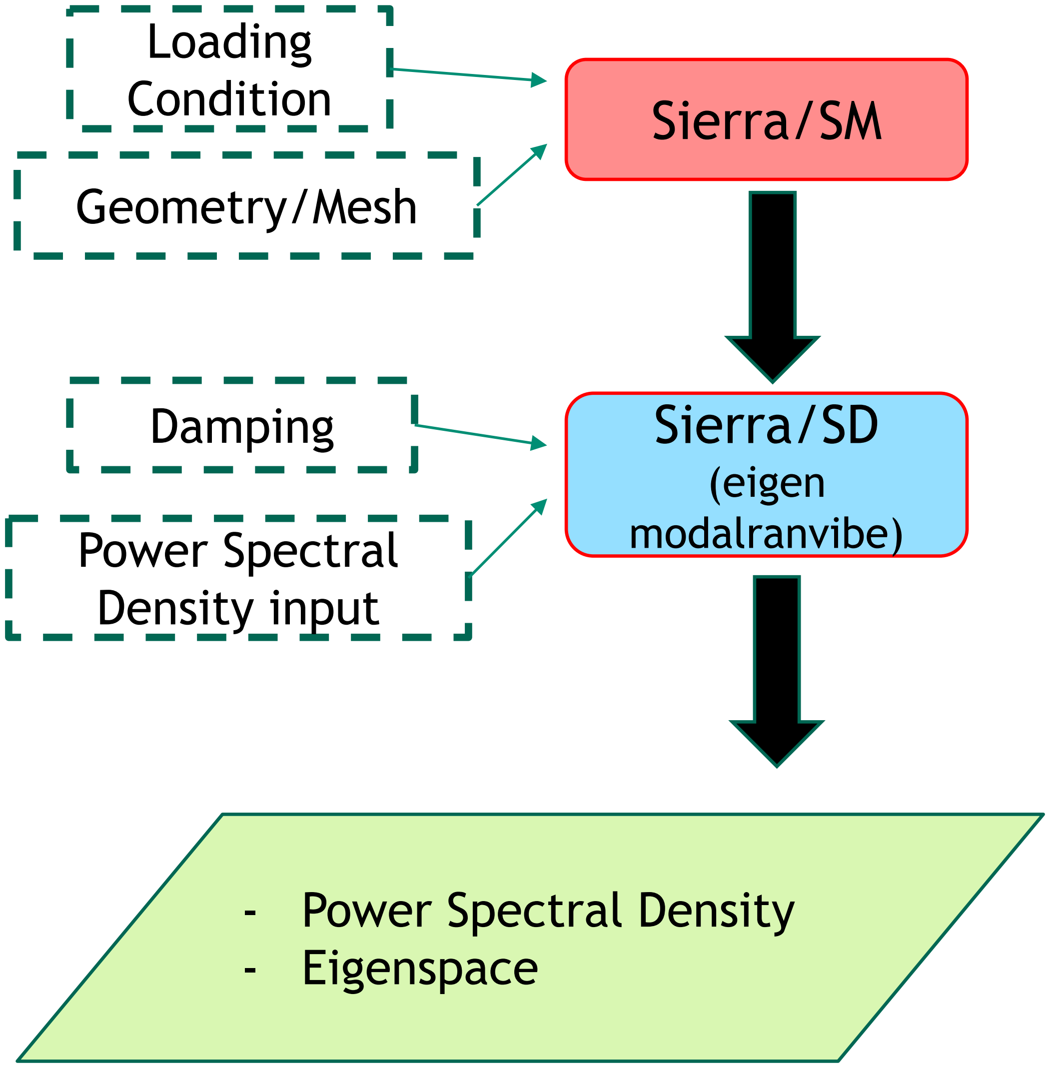






Introduction – Project Goals and General Workflow

- Goals
  - Establish a computational model that validates modular foam experimental outcomes
  - Successfully preload the model in Sierra/Solid Mechanics and handoff the preloaded state for a modal and frequency response analysis in Sierra/Structural Dynamics
  - Investigate effects of various preloading conditions on the modal response



Modeling Additively Manufactured Soft Foams – Hyperfoam

Storaker (Hyperfoam) compressible hyperelastic model [3]

$$W(\lambda_1, \lambda_2, \lambda_3) = \Sigma_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2}\left[\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3 + \frac{1}{\beta_i}\left(J^{-\alpha_i\beta_i} - 1\right)\right]$$

- Strain energy density dependent on principal stretch ratios (λ_k)
- Compressibility of each order: $\beta_i = \nu_i/(1 - 2\nu_i)$
- The order, N, determines how many parameters are needed
  - For each order, α_i, μ_i, and ν_i need to be estimated
  - If $N = 3$, a total of 9 parameters need to be estimated
  - If N =1, $\alpha_1 = -2$, $\mu_1 = \mu$, and $\nu_1 = 0.25$, the Blatz-Ko model is recovered

Blatz-Ko compressible hyperelastic model [4], is advantageous in that it has one free parameter

- Blatz-Ko is the Sierra/SD substitute for the Foam Damage model [5] available in Sierra/SM

$$W(\lambda_1, \lambda_2, \lambda_3) = \frac{\mu}{2}\left(\frac{\lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_3^2\lambda_1^2}{J^2} + 2J - 5\right)$$

Stress is related to strain energy density

$$\tau_{ij} = \lambda_k \frac{\partial W}{\partial \lambda_k}$$

Modeling Elastomer Potting Materials – Hyperelastic

Gent model [6]

$$W(\lambda_1, \lambda_2, \lambda_3) = -\frac{\mu J_m}{2} \ln\left(1 - \frac{\lambda_1^2 + \lambda_2^2 + \lambda_3^2 - 3}{J_m}\right)$$

- Strain energy density dependent on principal stretch ratios (λ_k)
- Limit on extensibility: J_m
- Letting $J_m \rightarrow \infty$ recovers the Neo-Hookean model

Neo-Hookean model [7]

$$W(\lambda_1, \lambda_2, \lambda_3) = \frac{\mu}{2}(\lambda_1^2 + \lambda_2^2 + \lambda_3^2 - 3).$$

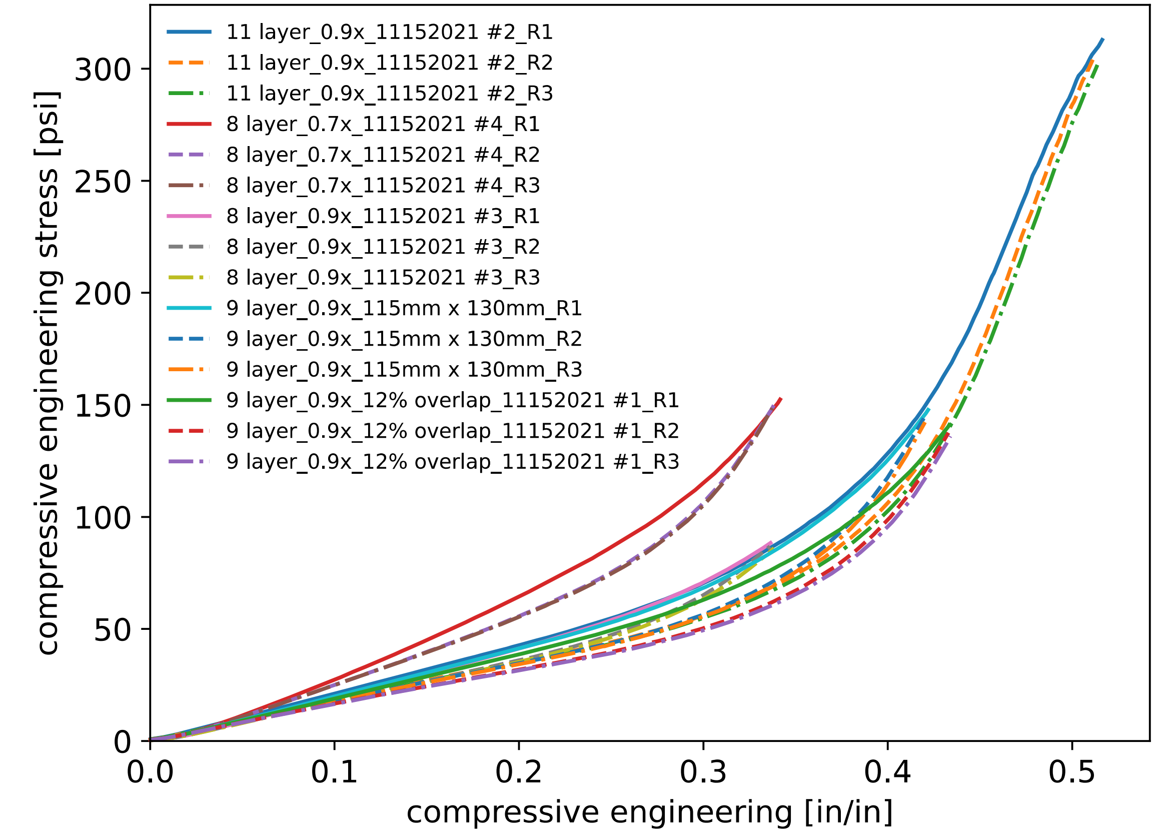
Stress is related to strain energy density

$$\tau_{ij} = \lambda_k \frac{\partial W}{\partial \lambda_k}$$

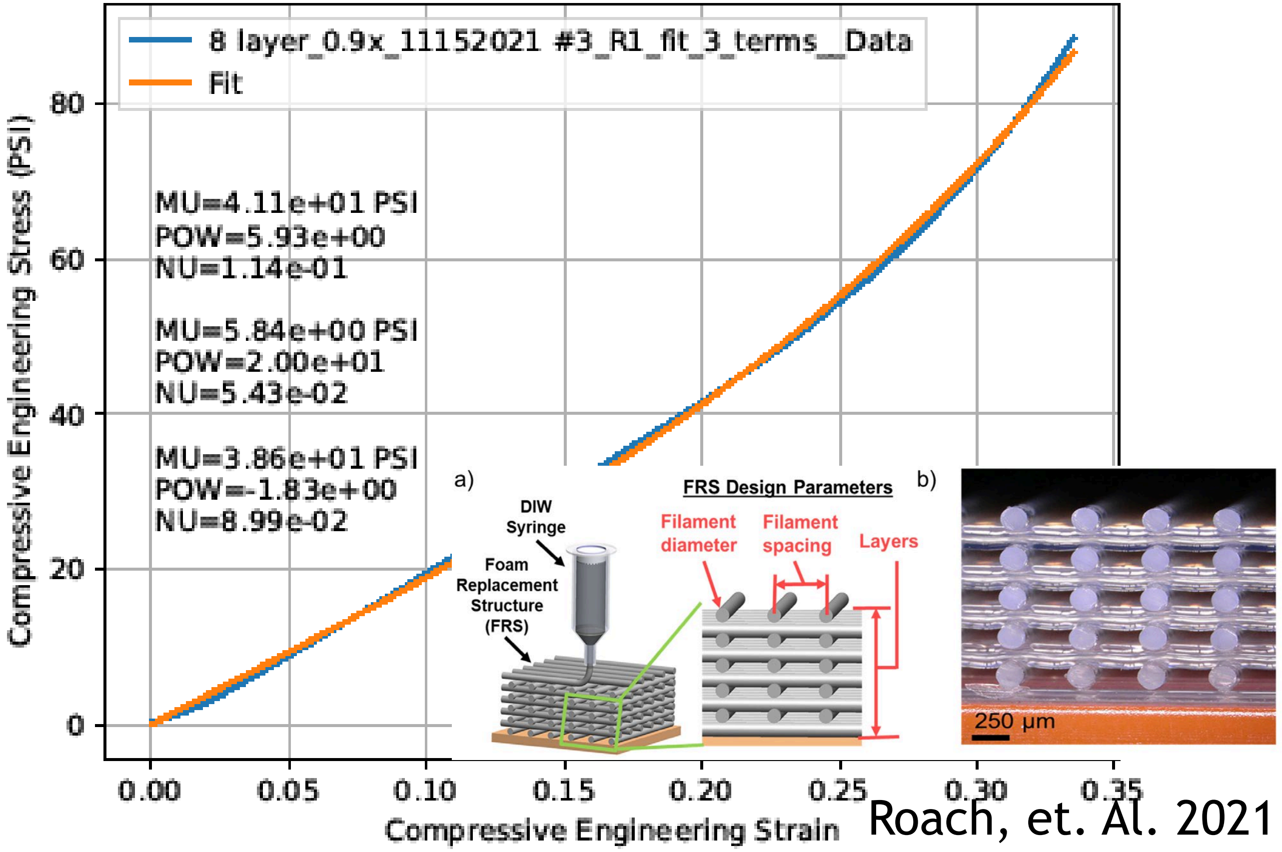
Soft AM Lattice Hyperfoam Model Parameter Estimation

- Perform uniaxial compression tests on the DIW lattice
- Estimate parameters based on desired order number and optimization criteria
- DIW lattice can be modeled as a homogenized solid (no lattice structure) with the mechanical behavior due to the lattice's structure
- Each DIW lattice has length scale dependent mechanical behavior

Collection of 0-45-90-135-180 DIW Compression Tests



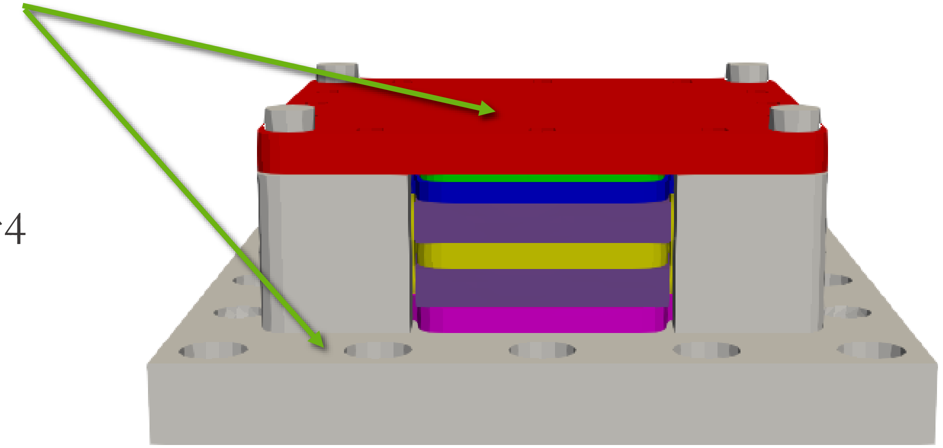
Hyperfoam fitting of an 8 Layer, 0.9x Spacing Lattice



Roach, et. Al. 2021

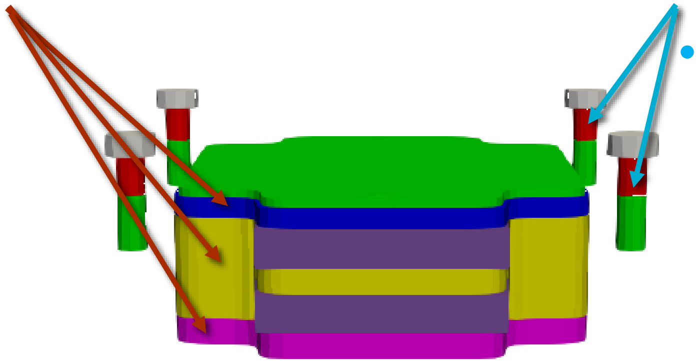
Methods- Material Modeling

- Base and Lid of fixture modeled using 6061 Aluminum
- Linear Elastic Model
  - **Youngs Modulus** 1000 ksi
  - **Poissons Ratio** 0.33
  - **Density** 2.5e-04 lbf*s^2/ in^4



Methods- Material Modeling

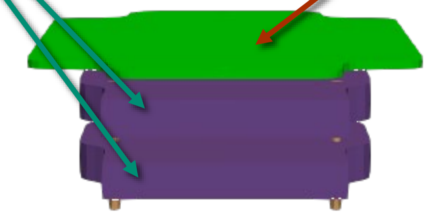
- Rigid Housing: Modular PMDI-10 Foam
- Foam Damage Model (SM)
  - Compressible hyperelastic material
  - Material properties are a function Of strain or temperature
  - Model parameterized by M. Neilsen (org 1558)
  - **Youngs Modulus** 12.8 ksi
  - **Poissons Ratio** 0.25
  - **Density** 1.65e-05 lbf*s^2/ in^4
- Blatz-Ko Model (SD)
  - Used as alternate model due to SD support issues
  - Similarly a compressible hyperelastic model



- Bolts: Plain Carbon steel
- Linear Elastic Model
  - **Youngs Modulus** 29,000 ksi
  - **Poissons Ratio** 0.29
  - **Density** 7.35e-04 lbf*s^2/ in^4

Methods- Material Modeling

- Electronics Conformal Coating: Sylgard 184
- Gent Hyperelastic Model (SM)
  - A nearly incompressible model for rubbery materials
  - **Youngs Modulus** 0.183 ksi
  - **Bulk Modulus** 133 ksi
  - **Density** 9.17e-05 lbf*s^2/ in^4
- Neo-Hookean Hyperelastic Model (SD)
  - Used as alternate model due to SD support issues
  - At low strains the models are nearly equivalent

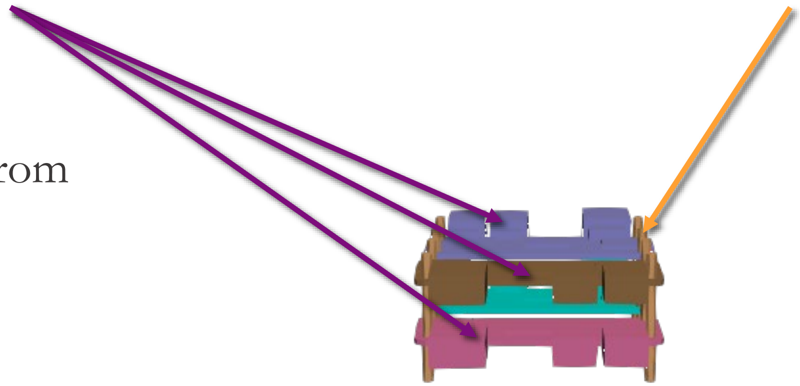


- Compression Pad: DIW printed lattice
- Homogenized as Hyperfoam Model
  - Hyperelastic model for elastomeric foams
  - Density calculated based on lattice geometry
  - Strain energy density parameters dependent on the specific pad being looked at :

```
Shear Modulus = 144.503254  # Initial Shear Modulus
Bulk Modulus = 135.626087  # Initial Bulk Modulus
#
N = 3
#
SHEAR = 9.113e+00 7.453e+01 6.086e+01
#
ALPHA = -8.118e+00 1.856e+01 2.538e+00
#
POISSON = 0.000e+00 0.000e+00 1.962e-01
```

Methods- Material Modeling

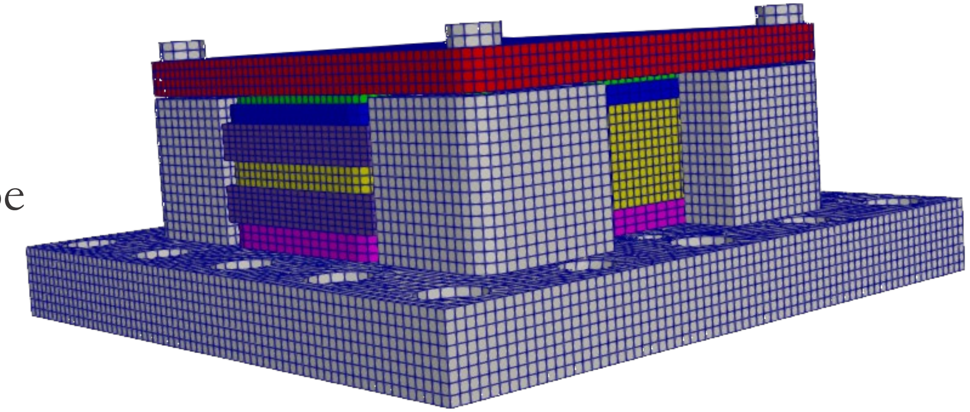
- Electronics : Raspberry Pi Zero
- Linear Elastic-Plastic
  - Model developed using data from FR408 circuit board tests
  - **Youngs Modulus** 4,351 ksi
  - **Poisson's Ratio** 0.3
  - **Density** 9.58e-05 lbf*s^2/ in^4
  - **Yield Stress** 21.8 ksi



- Electronic Support Pins : Steel
- Linear Elastic (same from previous slide)

Methods – (mesh, elements, BC, Loadings)

- Mesh includes 72,664 elements
- A uniform gradient element type was chosen for speed.



- Two different loadings were investigated:
  - Artificial strain in bolts
  - Prescribed displacement in the lid

- Two different BCs were investigated:
  - Fixed base in direction of loading
  - Inertia Relief on the base in direction of loading
- Temperature was fixed at 300 K

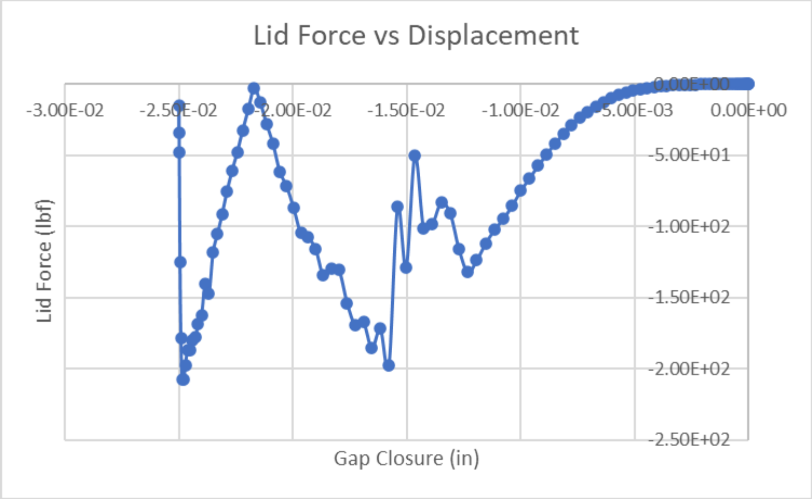
Methods – (SM specifics)

- The Handoff to SD
  - Addition of stiff beam and concentrated mass
  - Material Incompatibilities
  - Exporting the proper state from the exodus file

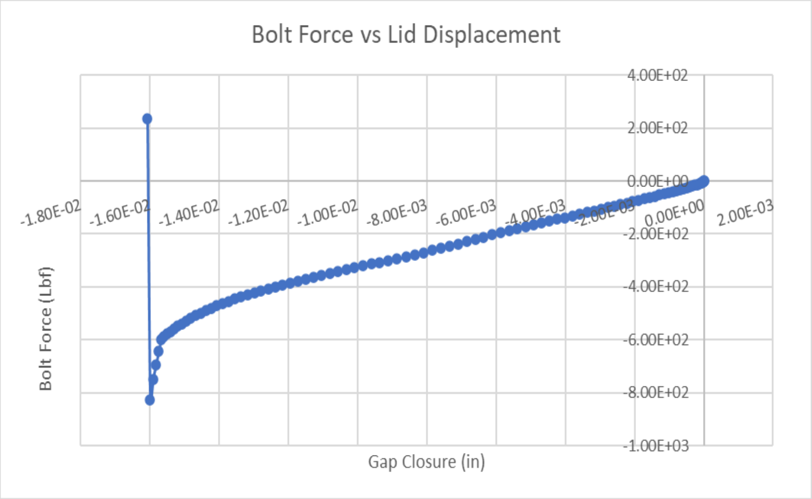
- Computational Cost
  - The full model with no modifications takes 12 hours
  - Addition of Mass scaling for certain parts of the assemblies
  - After mass scaling validation, reduction of exec time to 45 min-1 hr

- Contact, Contact, Contact
  - Many blocks in contact, what's the best way to define the contact model?
  - Adopted a friction model for tangential contact and general contact for normal
  - Constraint formulation had to be changed to fix contact issues

Results - (SM Loading Strategies)

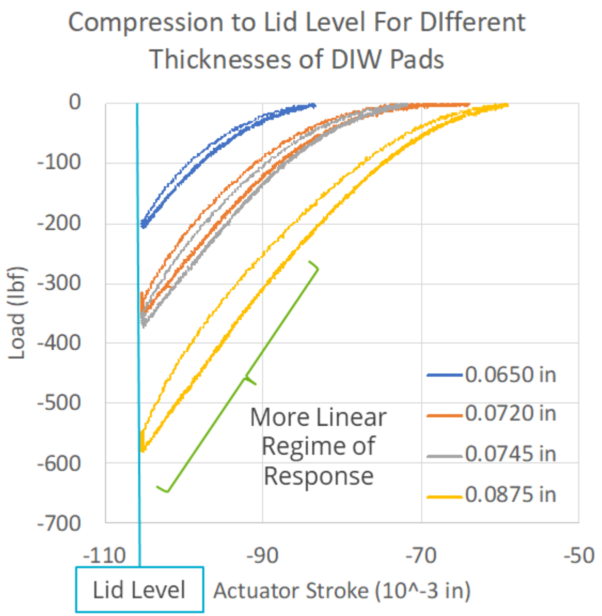


.0650" pads

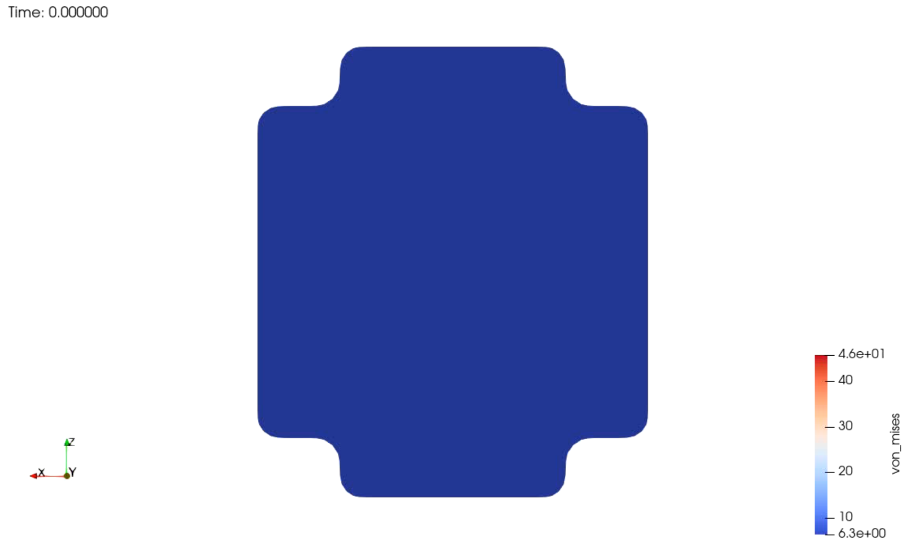


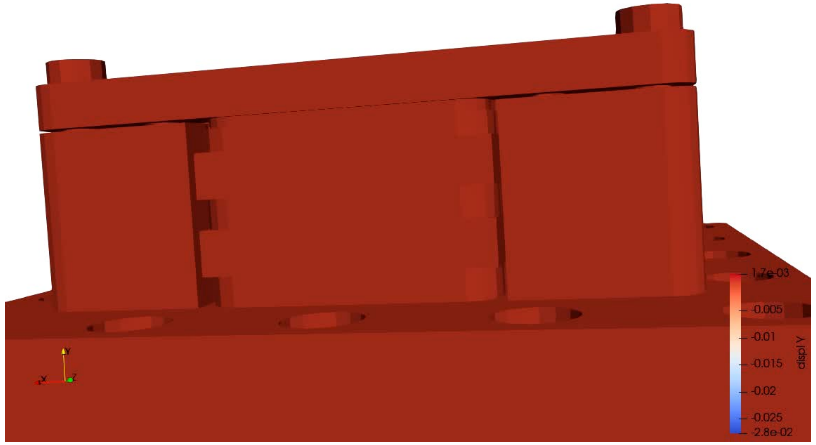
- What is going on when the gap is *almost* closed?

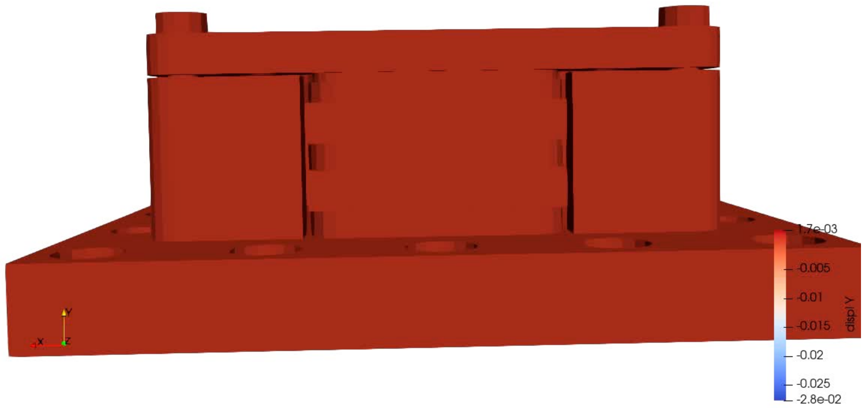
- Which loading strategy is better?

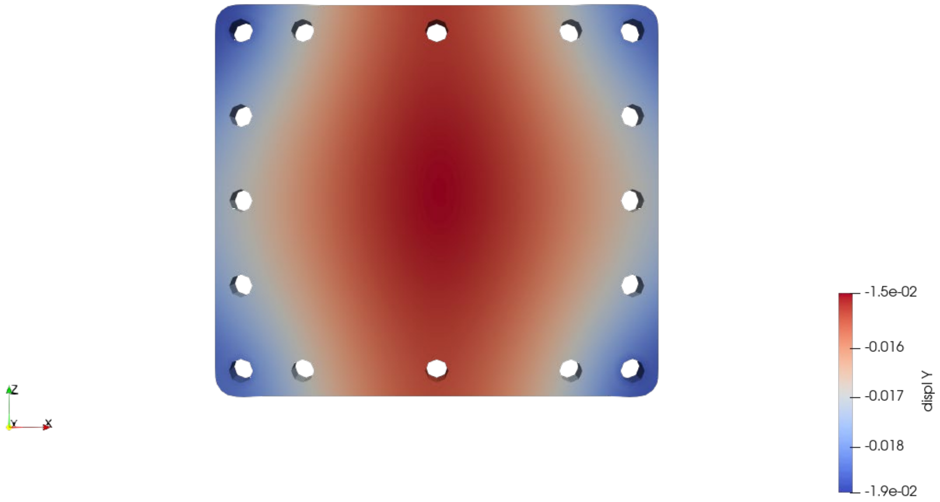


Results - (SM contour plots)









Methods - (SD specifics)

- Application of acceleration input

Concentrated mass at end of rigid bar tied to base → Force is applied to concentrated mass → Desired acceleration is applied to base

- Cases and Parameters

Eigen Analysis: 300 modes up to 3000 Hz → Modal Random Vibration Analysis 0.01 g^2/Hz to 2kHz → Post Processing

- Tuning

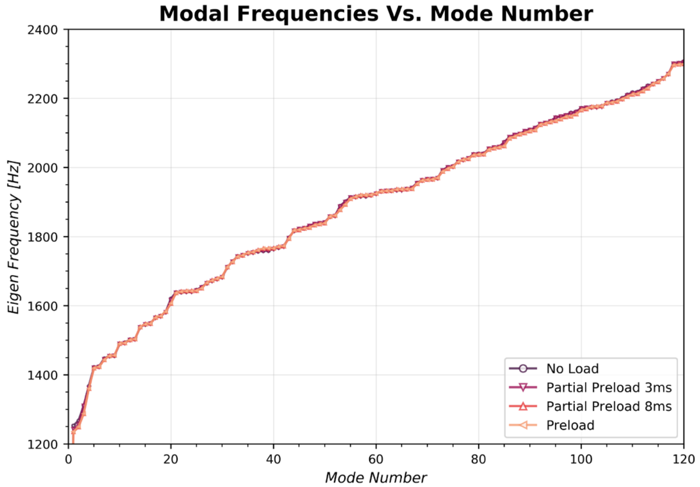
Global Damping: 2 % + First Dominant Mode Damping: 5 % + Second Dominant Mode Damping: 3.25 %

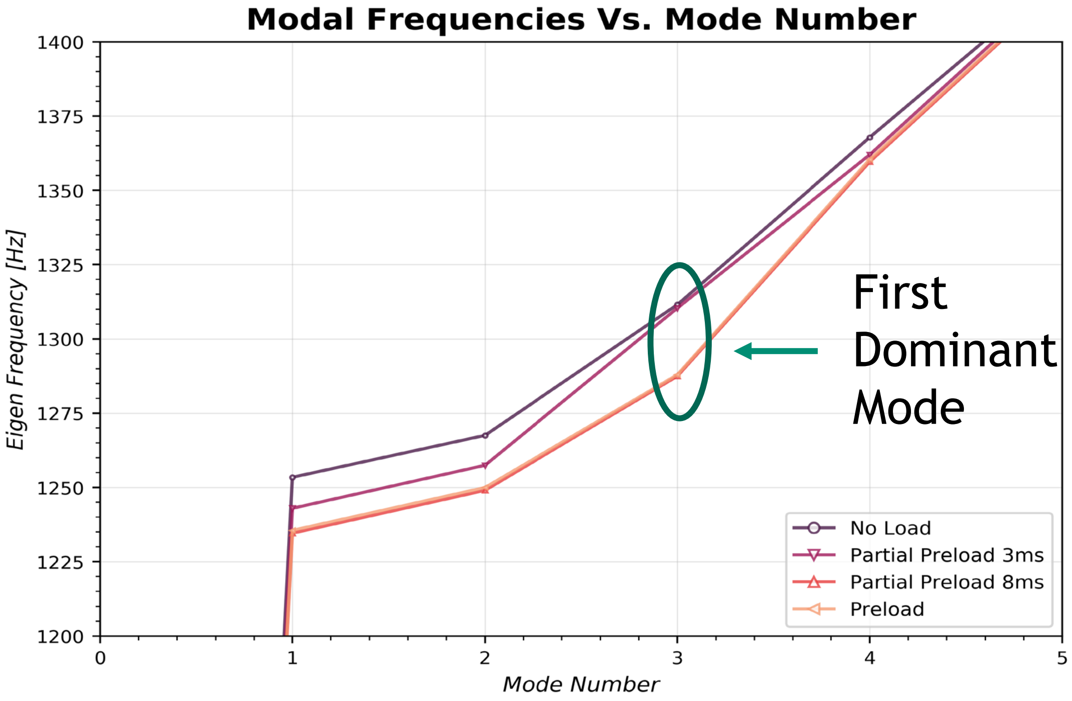
Results – Eigenfrequencies & Eigenmodes

- Similar eigenspace for each loading condition
  - Small differences between the frequencies for respective modes

- The effects of preloading show an eigen frequency decrease (counter-intuitive)
  - Highlights the nonlinearities present in the assembly

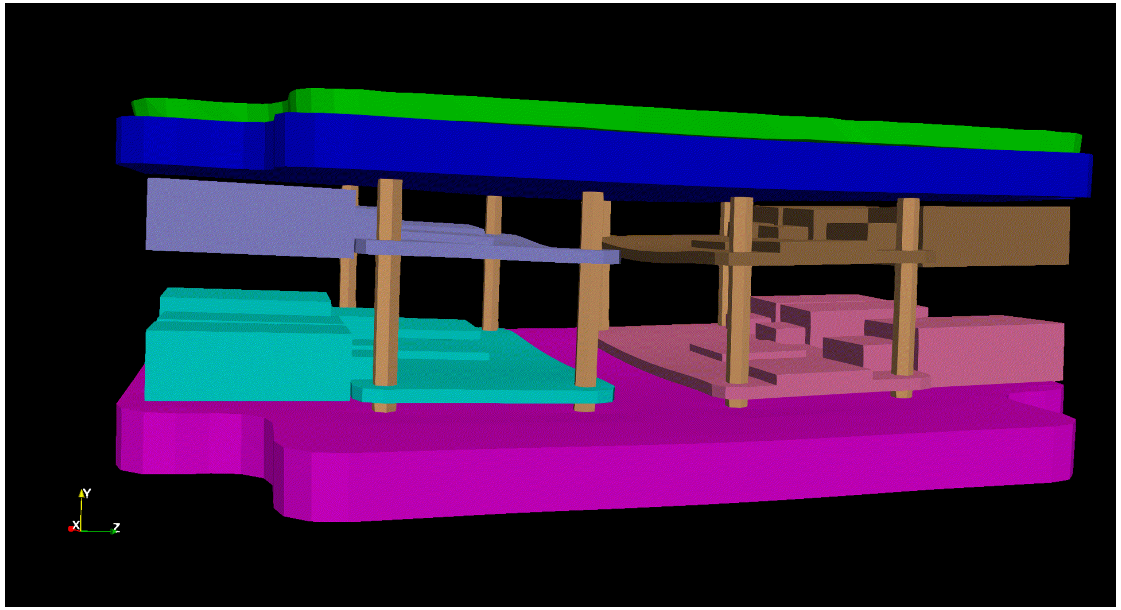
- Future work should investigate the effects of lattice structure and layer count on the eigenspace as well

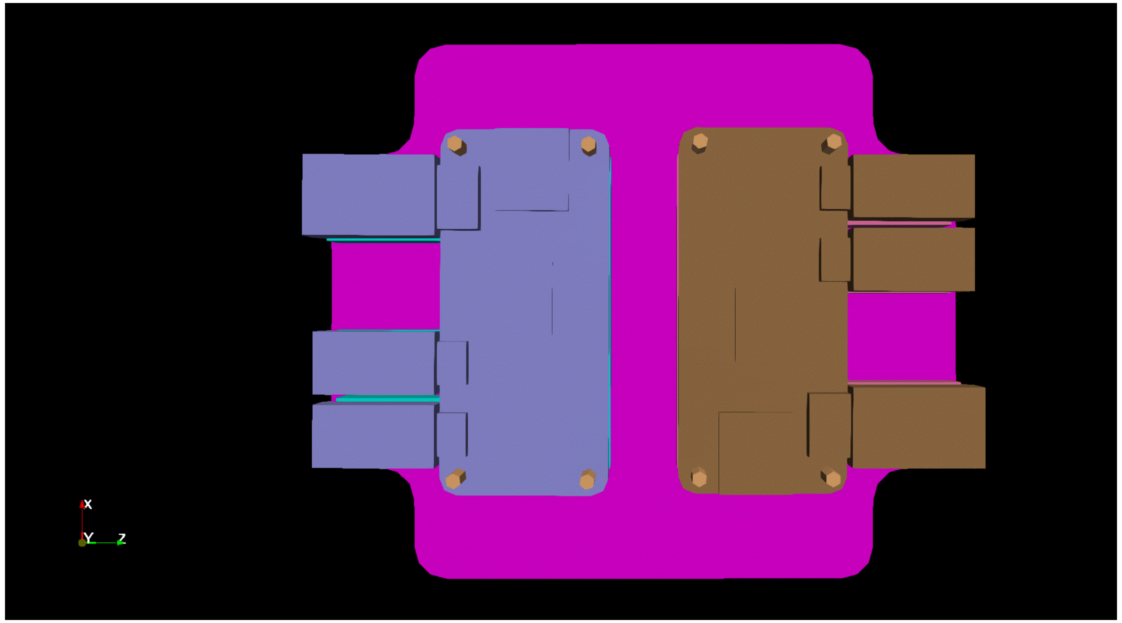




Results – Dominant Modes

- Dominant mode (4)
  - ≈ 1320 Hz
  - Flexure in Raspberry Pi's along minor axis
- Second dominant mode (8)
  - ≈ 1443 Hz
  - Torsion about vertical axis coupled with flexure of each Raspberry Pi
- With a trusted model, methods to shift the frequency associated with dominant modes could be investigated



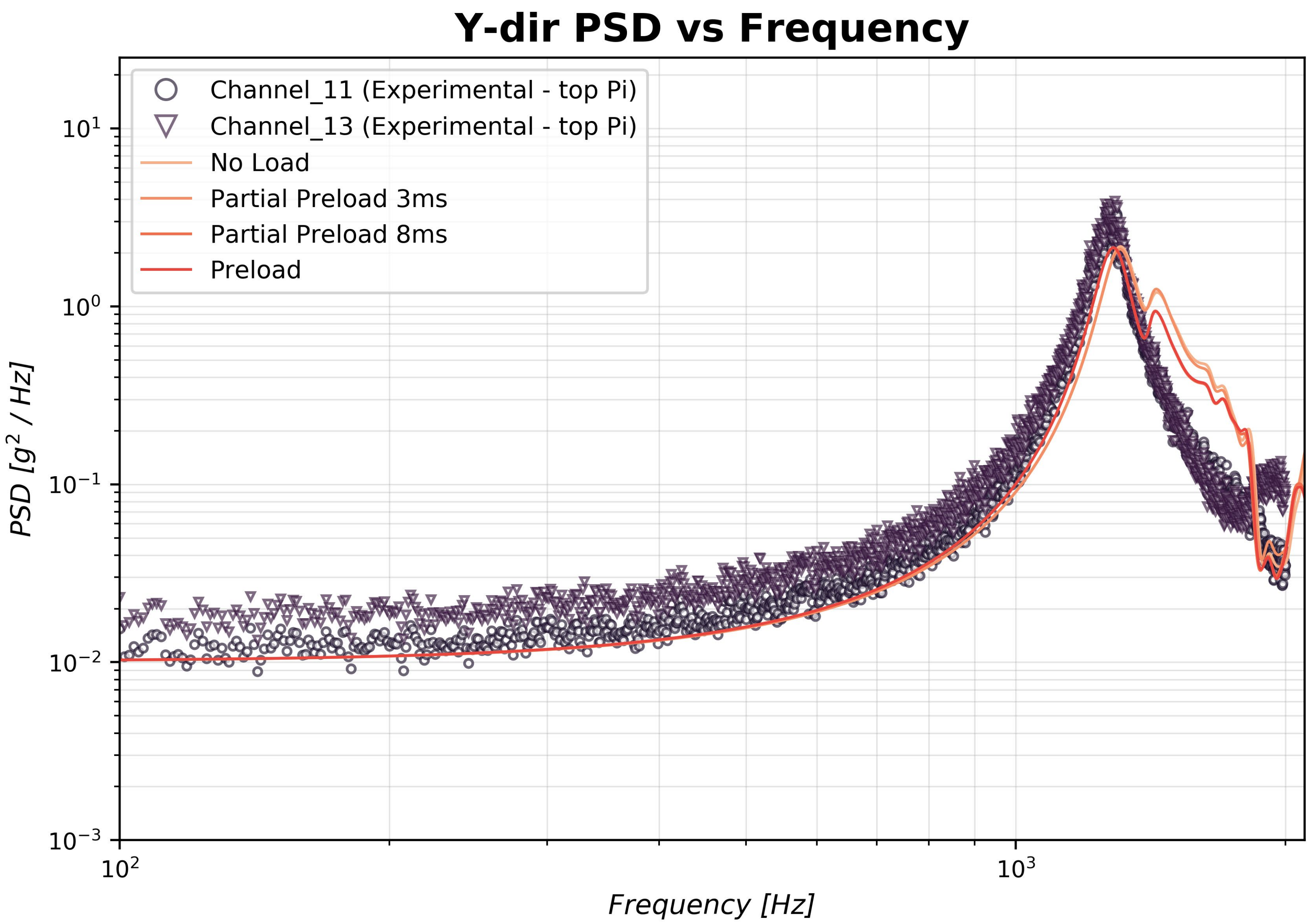


Results – PSD (Experimental vs Simulation)

- SM parameters
  - Cosramp input loading

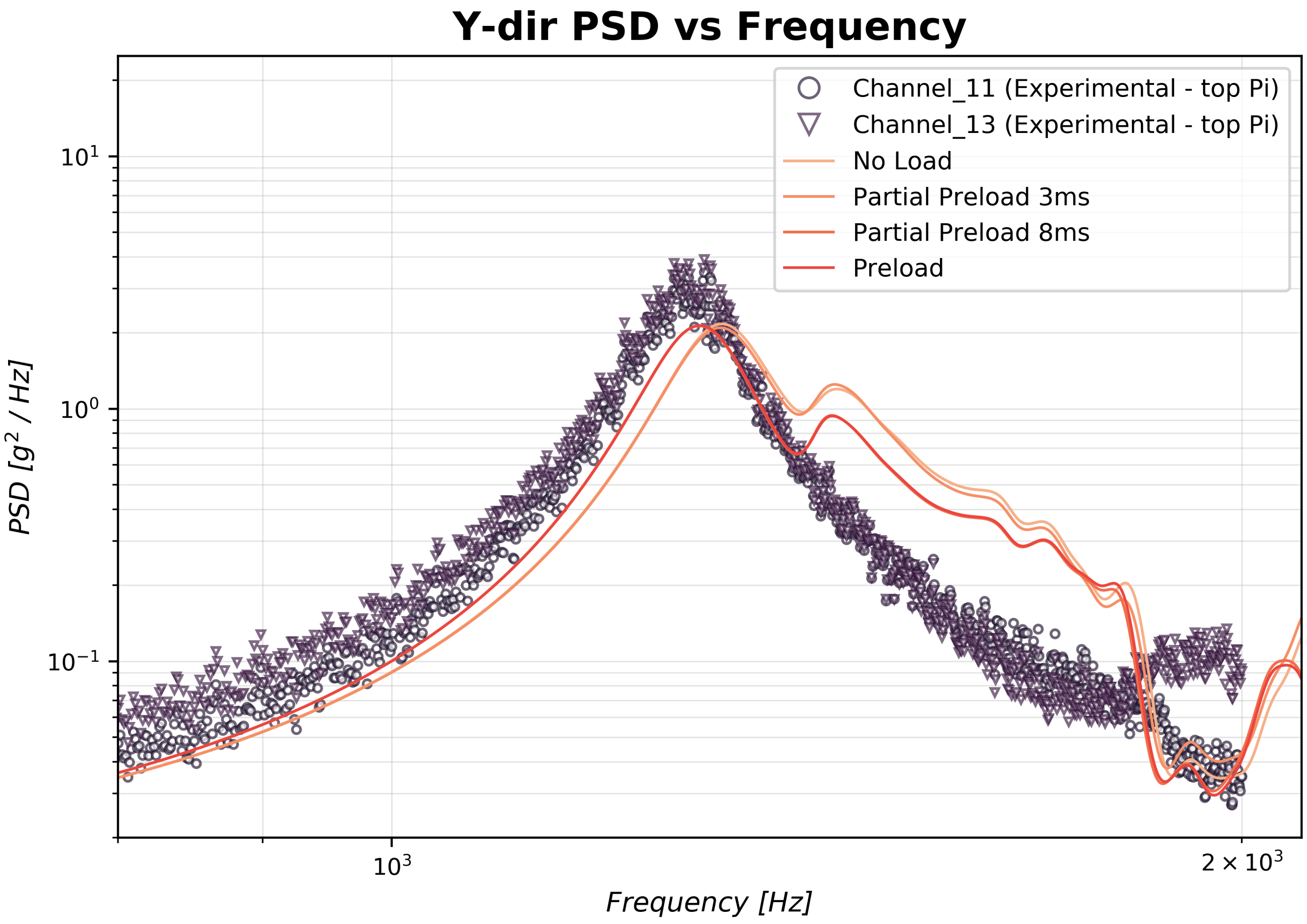
- SD MRV parameters:
  - 0.01 g^2/Hz input PSD
  - General contact = ON
  - 2% global damping
  - 5% total damping at first dominant mode
  - 3.25% total damping at second dominant mode

- Experimental damping:
  - 9.97% at 1233 Hz
  - 6.54% at 1458 Hz



Discussion

- Contact definition allows slipping between pads (no friction)
- Model refinement is possible with damping tweaks (requires ample time for SD "guess and check" runs)
- Potential sources of inconsistency
  - Homogenization
    - Lattice structures
    - Foams
    - Raspberry Pi
  - Cables/wires



Conclusion

- Preloaded structures modal response differs from standard structure
  - PSD peak for preloaded move down in frequency but magnitude remains the same

- SM to SD handoff is an involved process requiring many considerations during handoff
  - Not all material models available in SM are supported in SD
  - The SM model must accommodate the tools used by SD to excite the models

- Further work:
  - Run SD/SM analysis on other available lattices
  - Run SD with tied contact conditions
  - Further tune the model with modal damping parameters
  - Compare modular technique to traditional blown foam

References

[1] www.tayloredge.com/reference/Electronics/Capacitors/MLC_FailureMechanisms

[2] www.raypcb.com/reasons-for-pcb-resin-material-cracking-under-bga-pads-during-smt-processing/

[3] B. Storåkers, On material representation and constitutive branching in finite compressible elasticity, Journal of the Mechanics and Physics of Solids, Volume 34, Issue 2, 1986,

[4] Blatz, P. J., & Ko, W. L. (1962). Application of finite elastic theory to the deformation of rubbery materials. Transactions of the Society of Rheology, 6(1), 223-252.

[5] Lame Team. (2022). Library of Advanced Materials for Engineering 5.6, SAND2022-3247

[6] Gent, A. N. (1996). A new constitutive relation for rubber. Rubber chemistry and technology, 69(1), 59-61.

[7] Treloar, L. R. G. (1943). The elasticity of a network of long-chain molecules. I. Transactions of the Faraday Society, 39, 36-41.

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Thanks! Questions?