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Model Validation of Experimental Hardware: Design versus Reality

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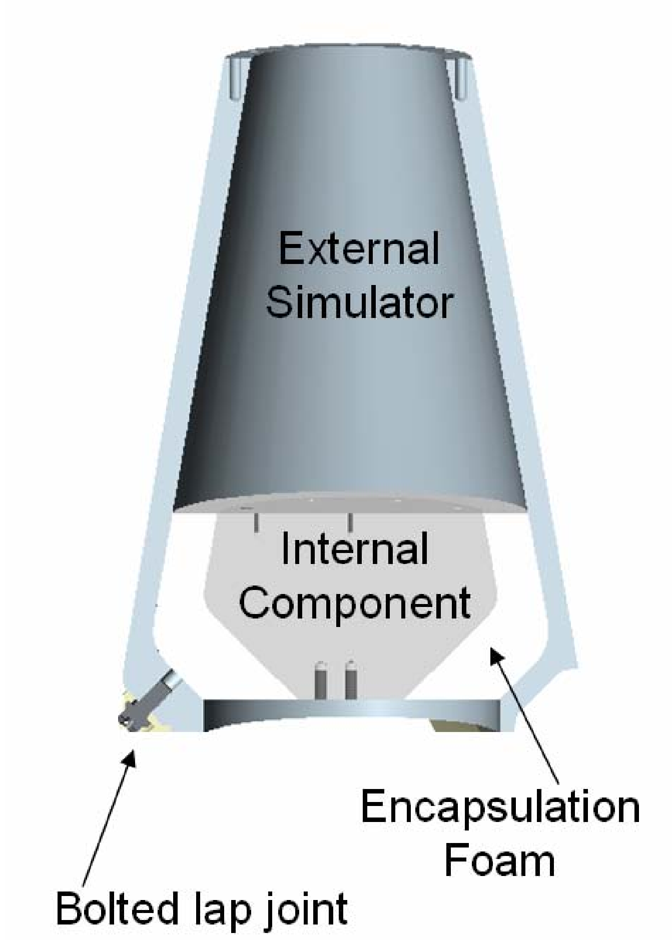
Introduction and Motivation

Model Validation Effort of Experimental Hardware

- Assess foam encapsulated components
- Bottom-up experimental approach
- Material → Subsystem validation levels
- Manufacturing process issues identified

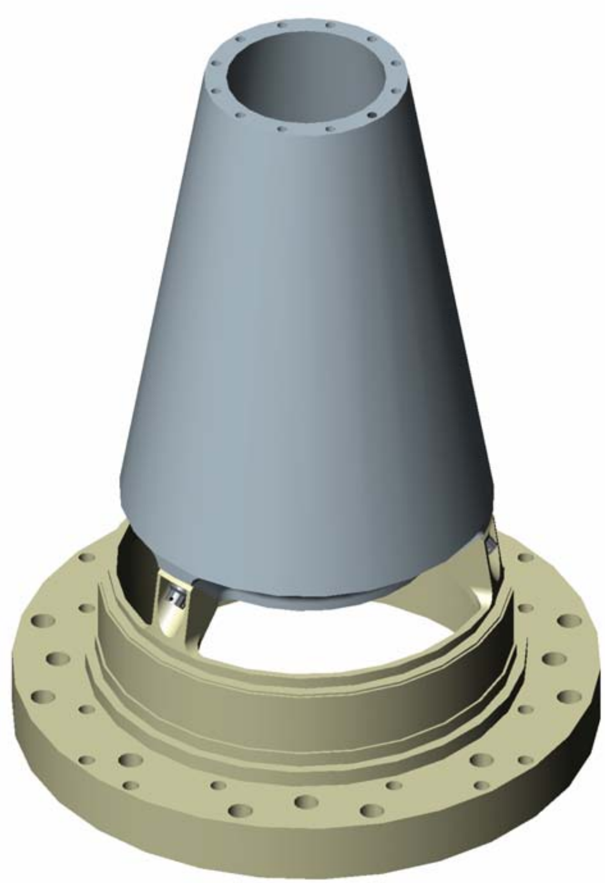


Introduction and Motivation

Model Development Considerations

- appropriate physics
- model form
- material parameters
- input loads
- boundary/loading conditions

Model Assumptions may be violated (reality ≠ design)



Introduction and Motivation

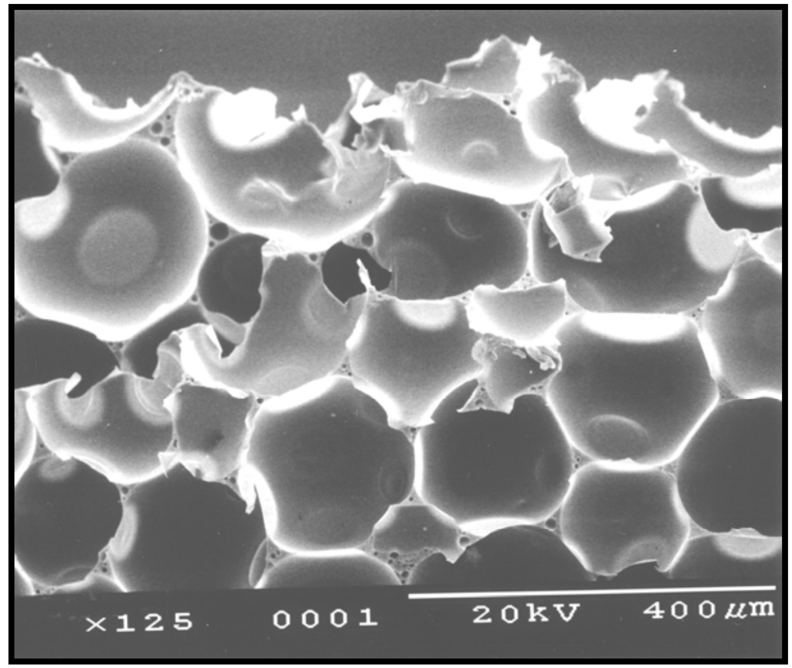
Formal Validation (triple-blind) Process

- Experimentalist
  - Collect validation data
  - No analytical model info
- Analyst
  - Develop FEA model
  - No experimental insight
- Independent party
  - Applied validation metrics

Introduction and Motivation

Foam Characteristics

- “rigid” epoxy foam
- closed-cell
- nominal density: 20 lb/ft^3
- mitigate shock and vibration
- average cell diameter ~200 µm
- modeled as linear viscoelastic



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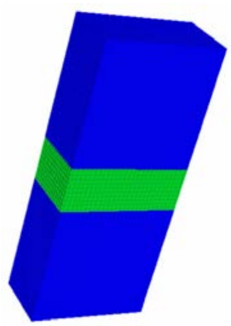
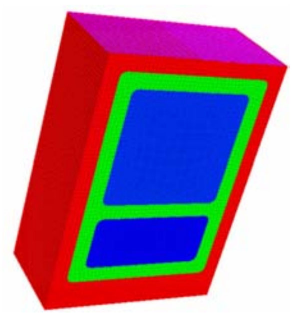
Model Development/Validation Process

Material/Component Validation		Benchmark Validation	Subsystem Validation
Phase 0	**Phase I**	**Phase II**	**LFU**
			
Constitutive	**Dumbbell**	**Rigid Component**	**Subsystem**

INCREASED COMPLEXITY

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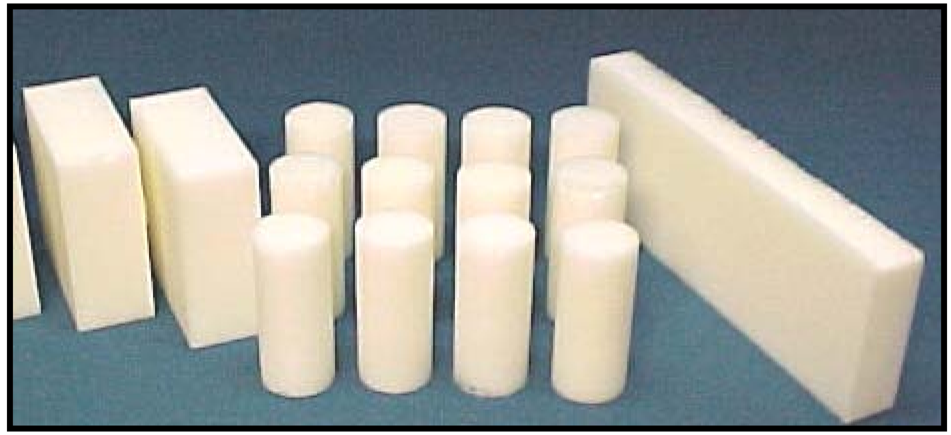
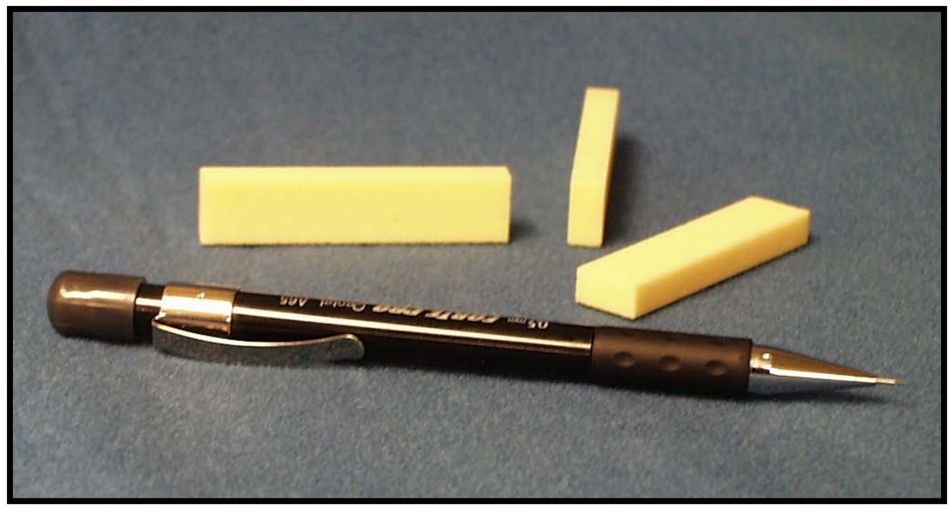
Material/Component Validation: Phase 0

Experimentally obtained material parameters

- Phase 0 geometry
- Quasi-static testing
  - tensile moduli
  - compressive moduli
- Temperature variation
  - glass transition (Tg)
  - rate dependence





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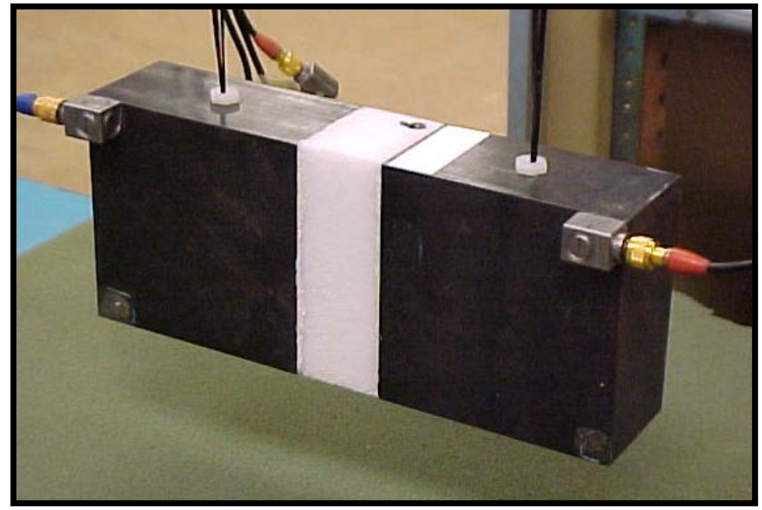
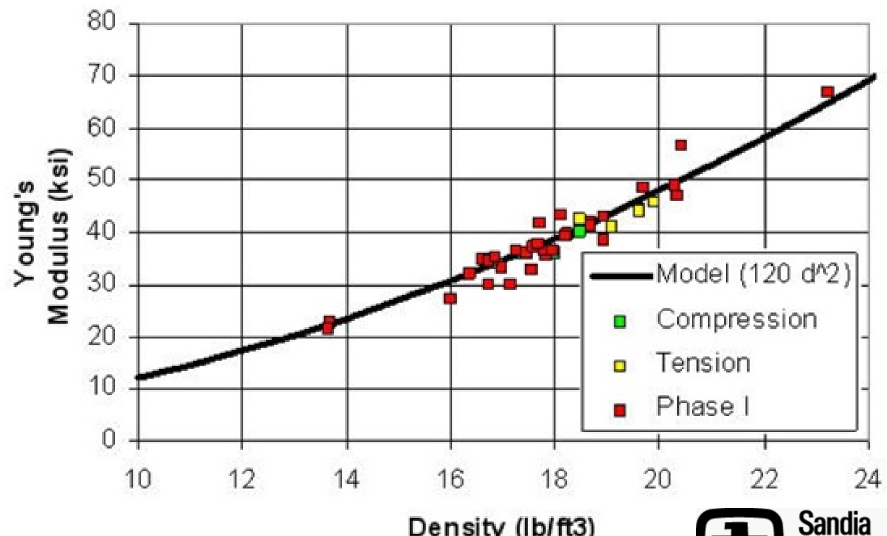
Material/Component Validation: Phase I

- **Linear viscoelastic model**
- **Phase I geometry**
  - **Modal analysis**
  - **Shaker vibration**
  - **Geometry variations**
- **Data used for both correlation and validation**
- **Model dependent upon density/gradient of foam**
- **Experimental E, ρ, ζ → Probabilistic model**





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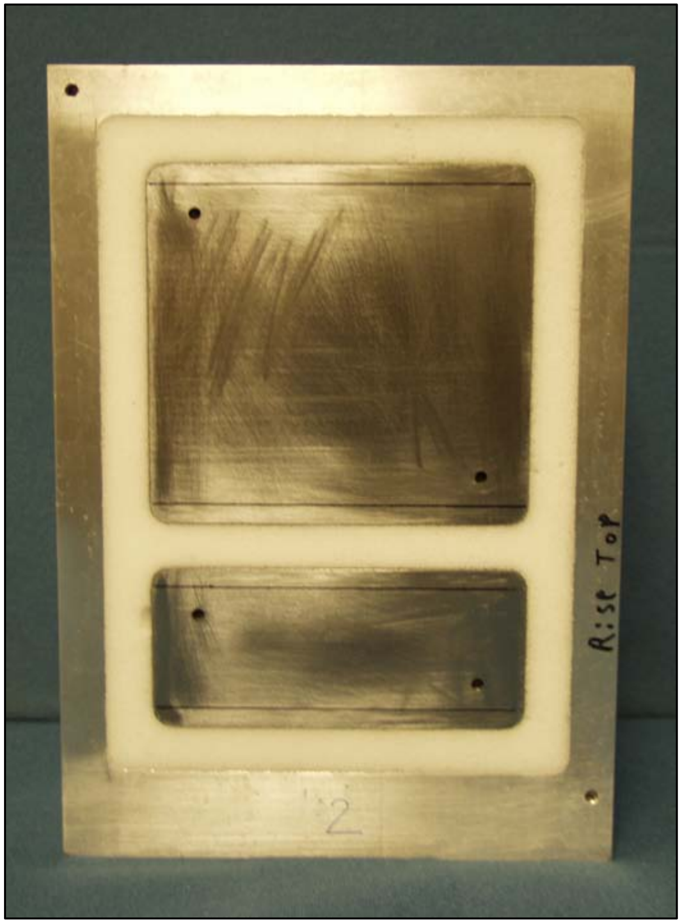
Benchmark Validation: Phase II

Phase II Geometry

- encapsulation foam
- outer aluminum mass
- stainless steel rigid interior masses
- natural adhesion of foam secured masses



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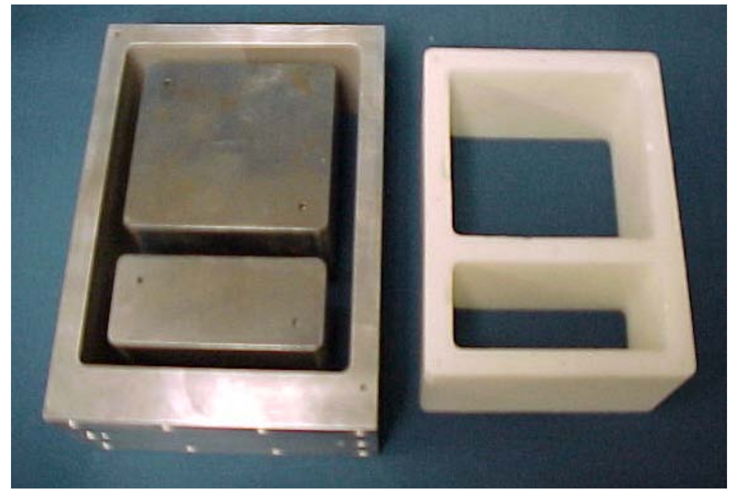
Benchmark Validation: Foam Development Study

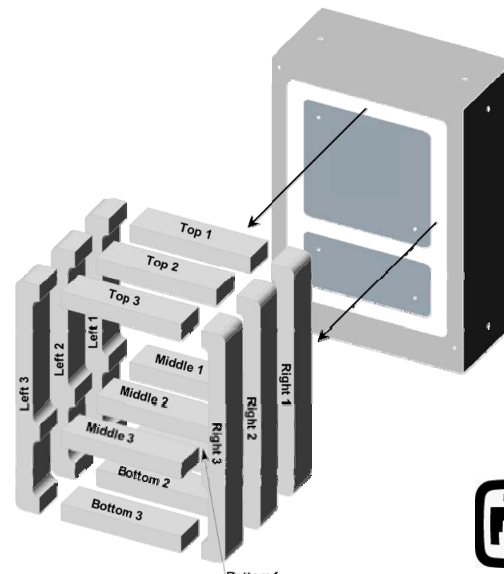
Define foaming process

- Minimize density variation
- Preheating
- Curing temp/time

Quantify average density and density gradient

- Mold release applied
- Density gradient observed along foam rise direction
- Average density = 20.2 lb/ft^3 (desired = 20 lb/ft^3)

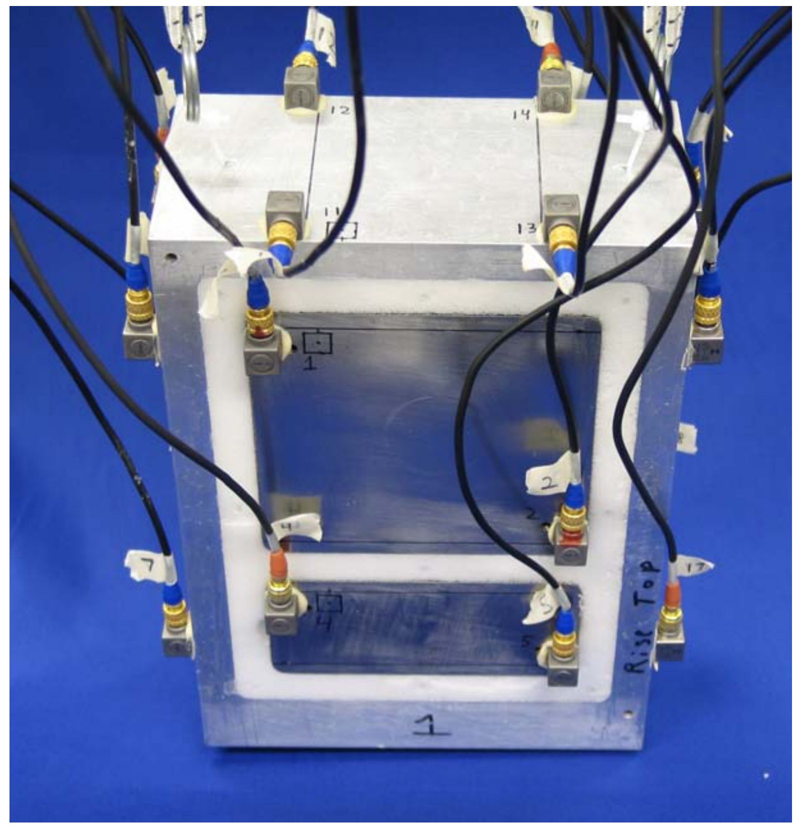




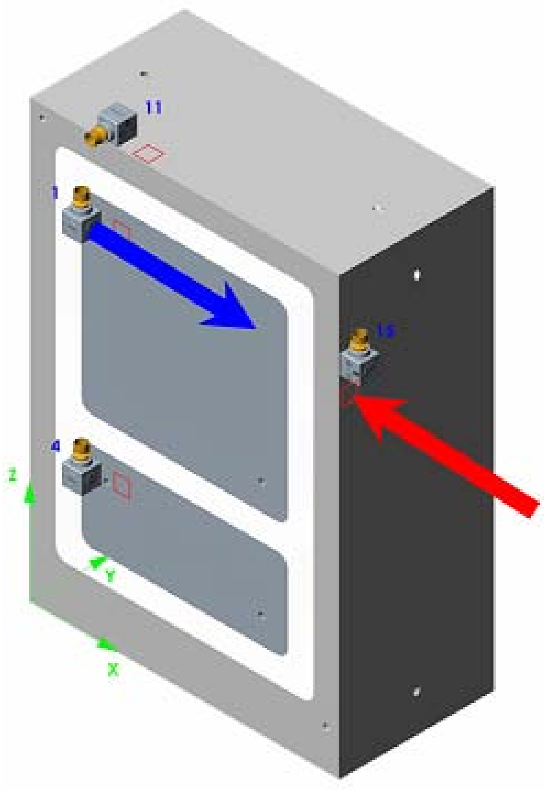
Benchmark Validation: Model Validation Data

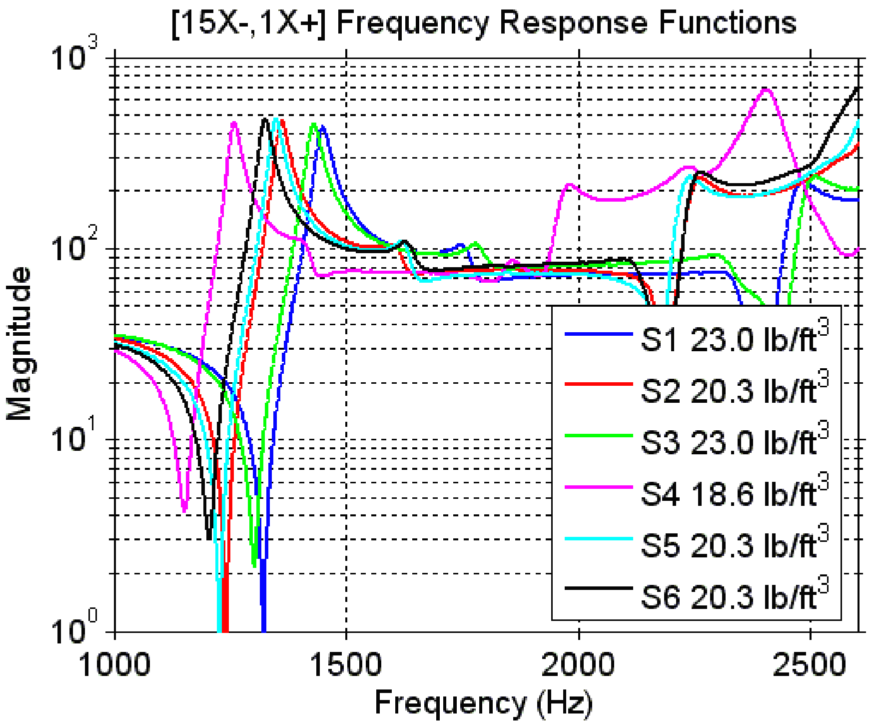
Validation samples created from studied foaming procedure

- Free-free modal
- Base-driven shaker
- Boundary conditions
- Input location effects
- Repeatability tests
- Mass loading effects examined



Benchmark Validation: Model Validation Data

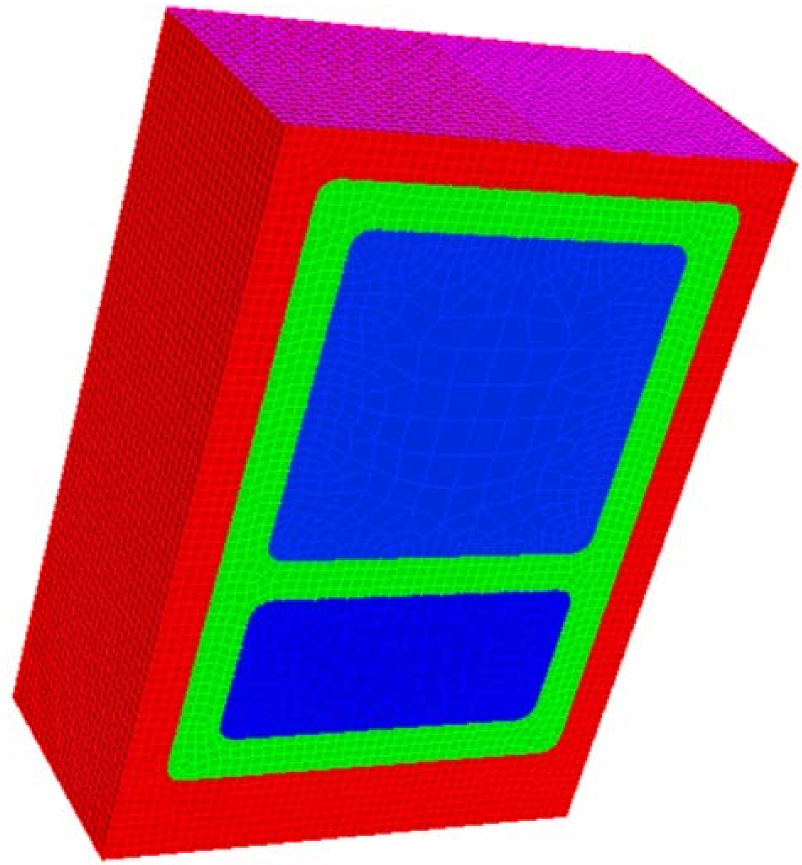




FRF displays similar general response, variations due to density variation

Benchmark Validation: Model Validation

- Two separate model validation assessments
  - Free-free modal and analytical data
    - FRF-based windowed metric applied
    - 80% of predictions must contain experimental results
  - Shaker time-domain vibration data
- Model validated



Angel Urbina, Thomas L. Paez, Brian Rutherford, Chris O'Gorman, Terry Hinnerichs and Patrick Hunter, **"Validation of Mathematical Models: An Overview of the Process"**, 2005 SEM Annual Conference, June 2005.

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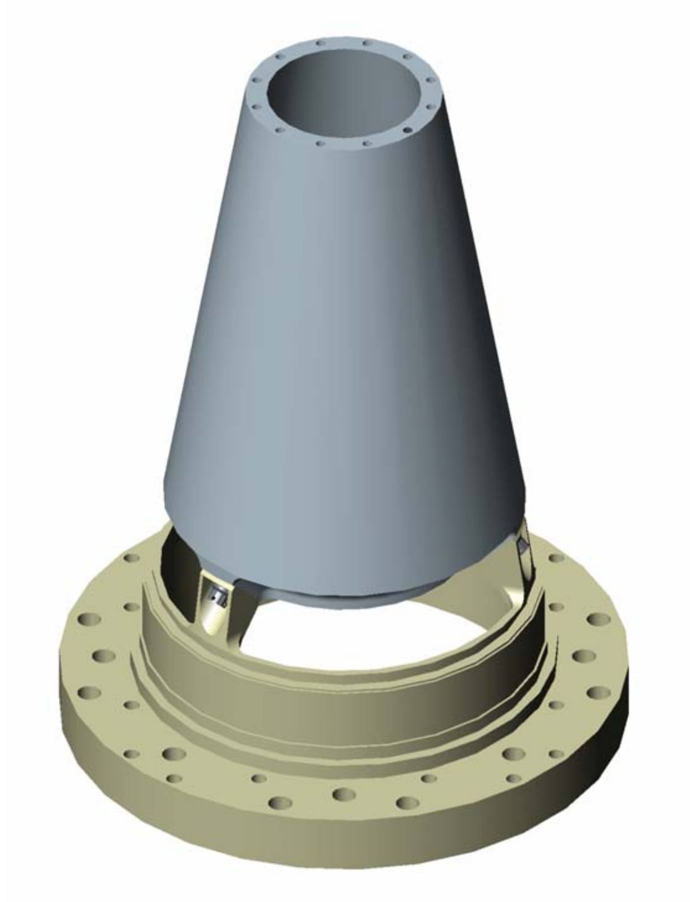
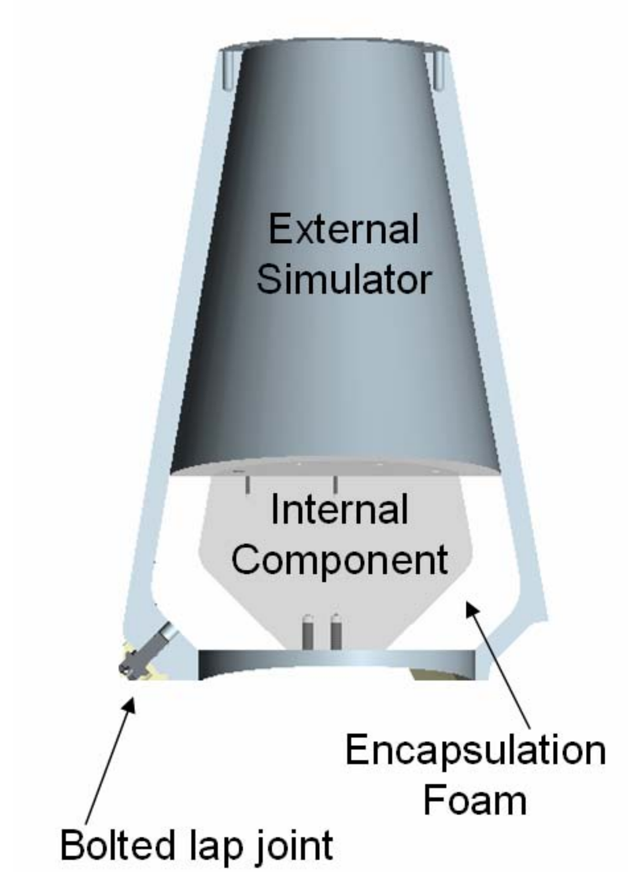
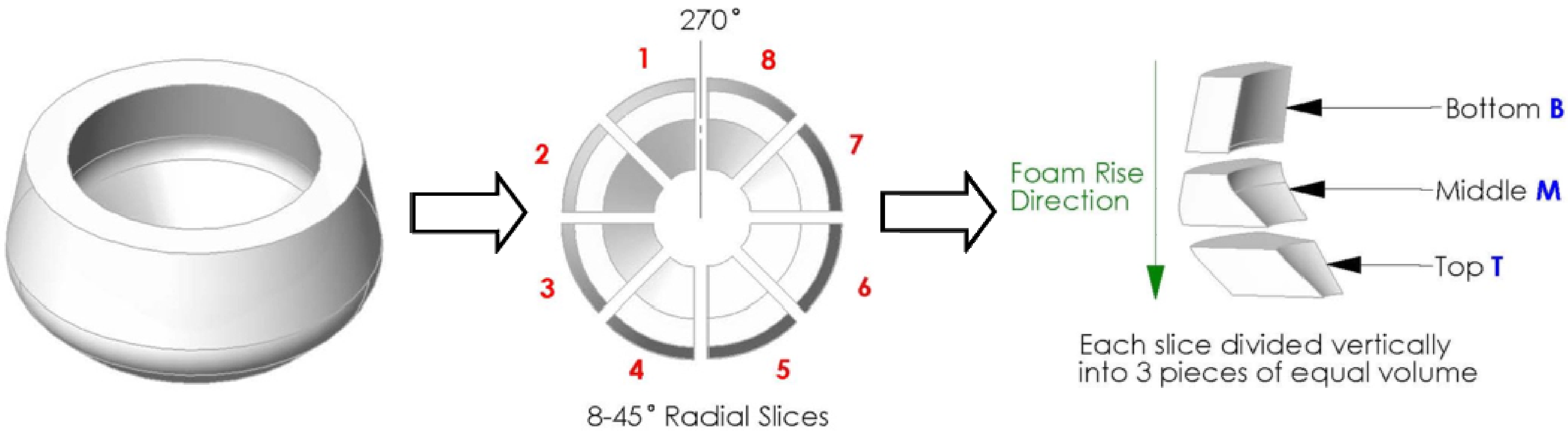
Low Fidelity Unit (LFU) Subsystem Validation





Merges two development efforts: foam & joint model

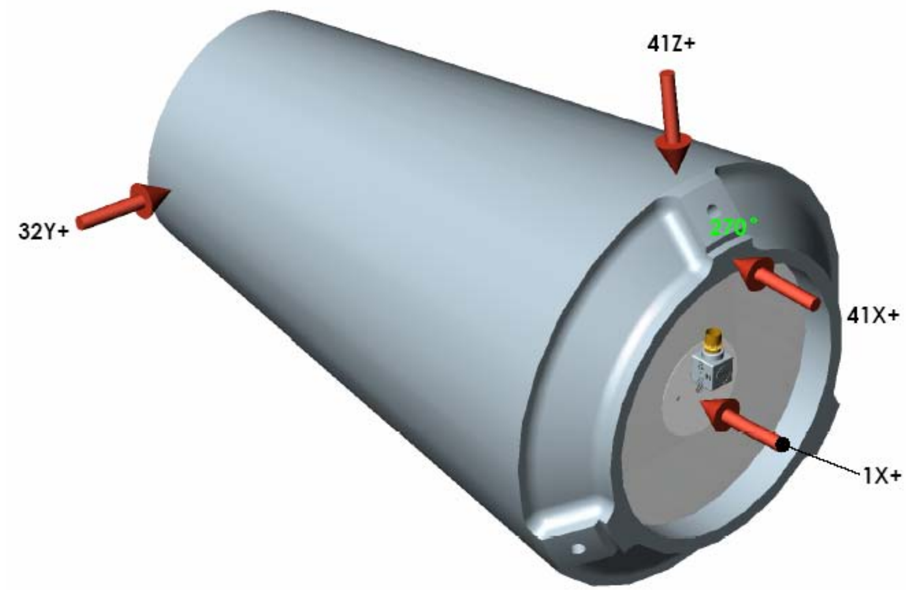
LFU Validation: Foam Development Study



Repeat density and gradient quantification:

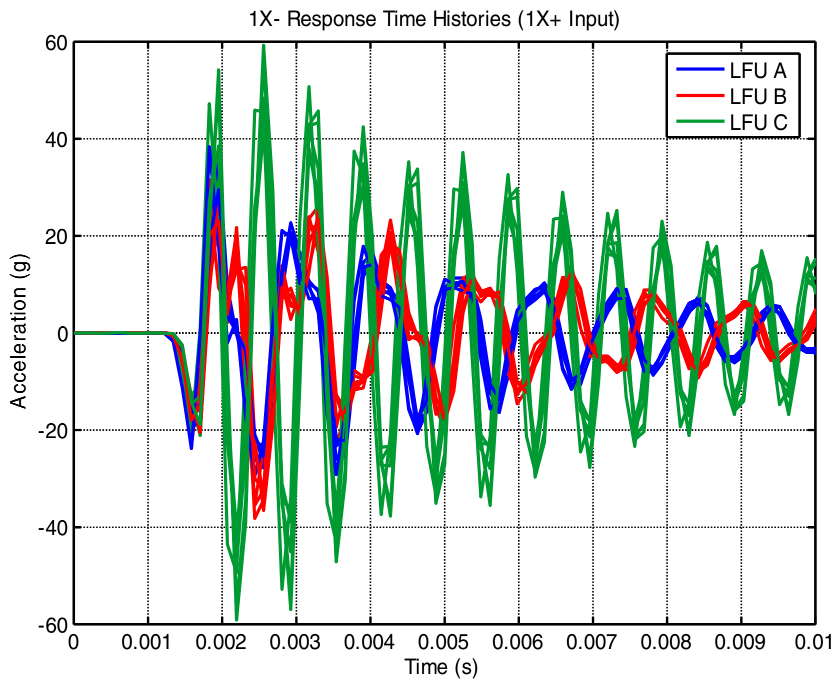
Average density 21 lb/ft^3, 19% gradient between sections

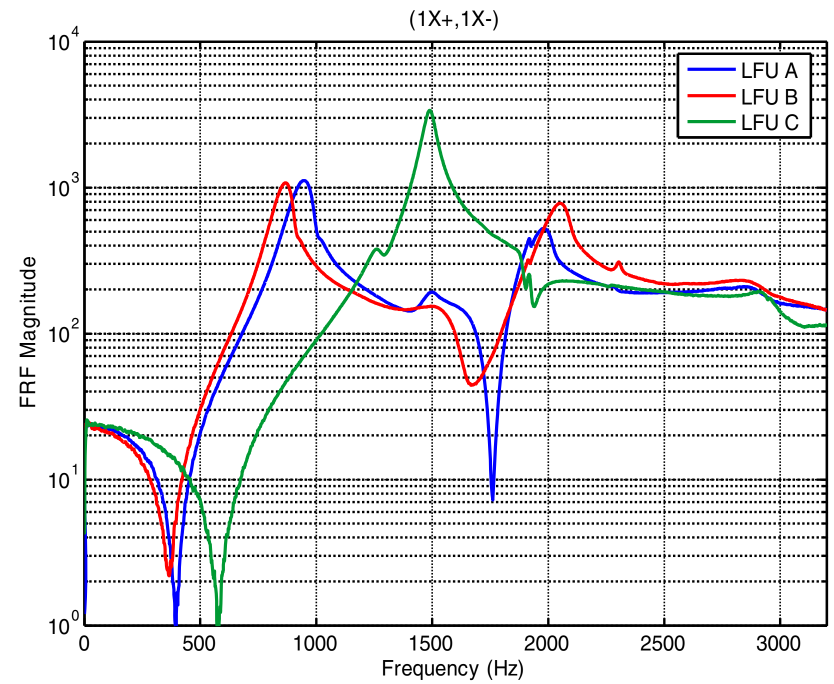
LFU Validation: Model Validation Data



Free-free modal test:
internal & external, orthogonal input

LFU Validation: Model Validation Data





Time History & FRF: results differed between samples, nonlinearities present, inconsistent with Phase II repeatability

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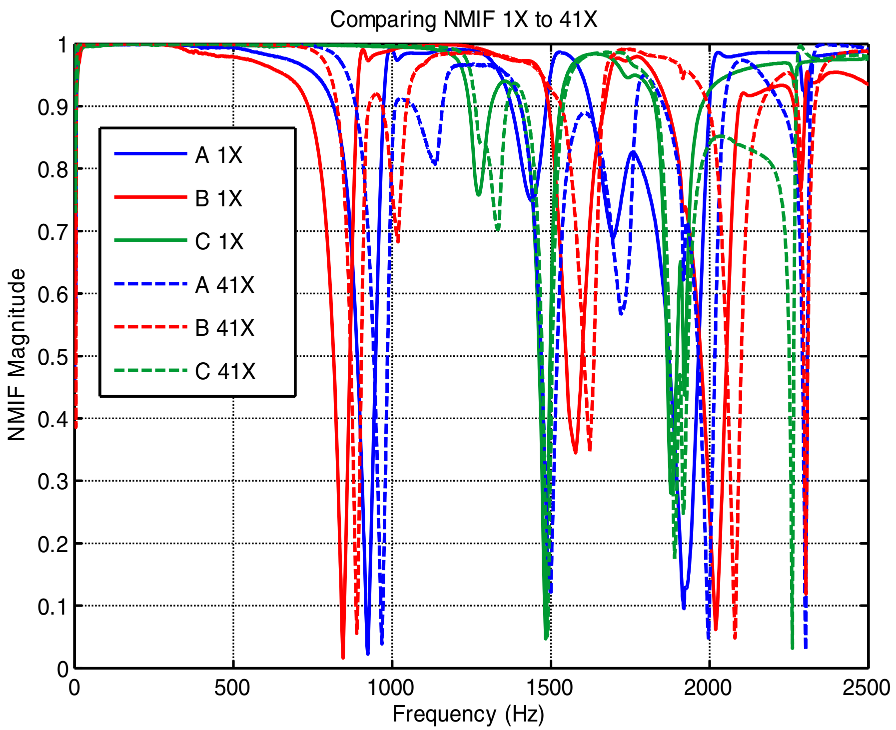
LFU Validation: Model Validation Data

- **Normal Mode Indicator Function Calculated**
  - **Shift of A,B: indicates nonlinearity present**
- **Mode Shapes Calculated**
  - **A,B axial mode w/rocking**
  - **C more axial**
- **Force/Displacement measured for sample C**
  - **effective (B.O.E.) stiffness > experimental stiffness**
- **Density variation does not account for frequency shift**



Solid – internal mass input

Dashed – external mass input

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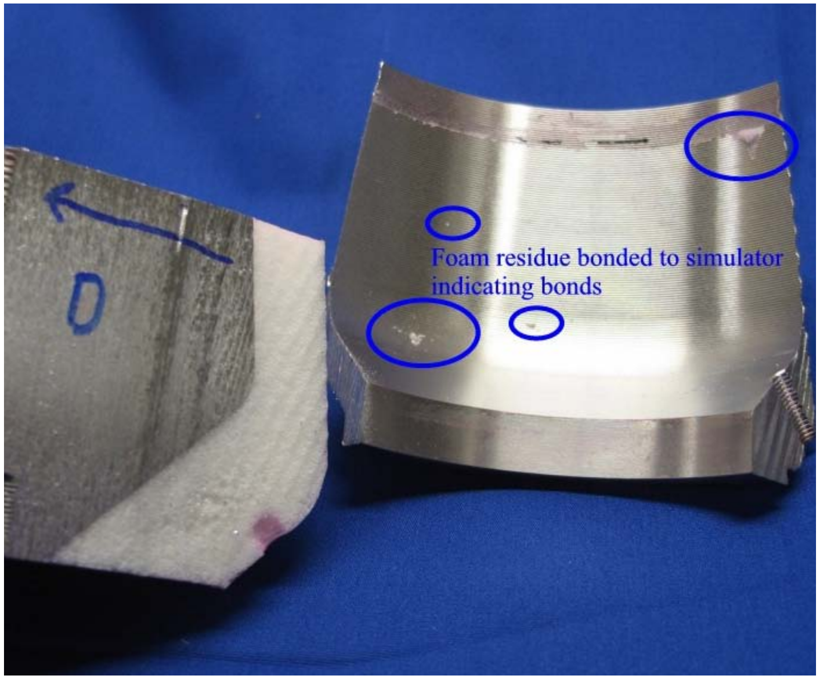
LFU Validation: Diagnostic Testing

- Two possible causes of behavior
  - Density variation
  - Interface bonding
- Diagnostic tests performed
  - NDE test, no results
  - Destructive test→
    very little bonding observed
- Lack of bonding cause of soft, non-linear behavior

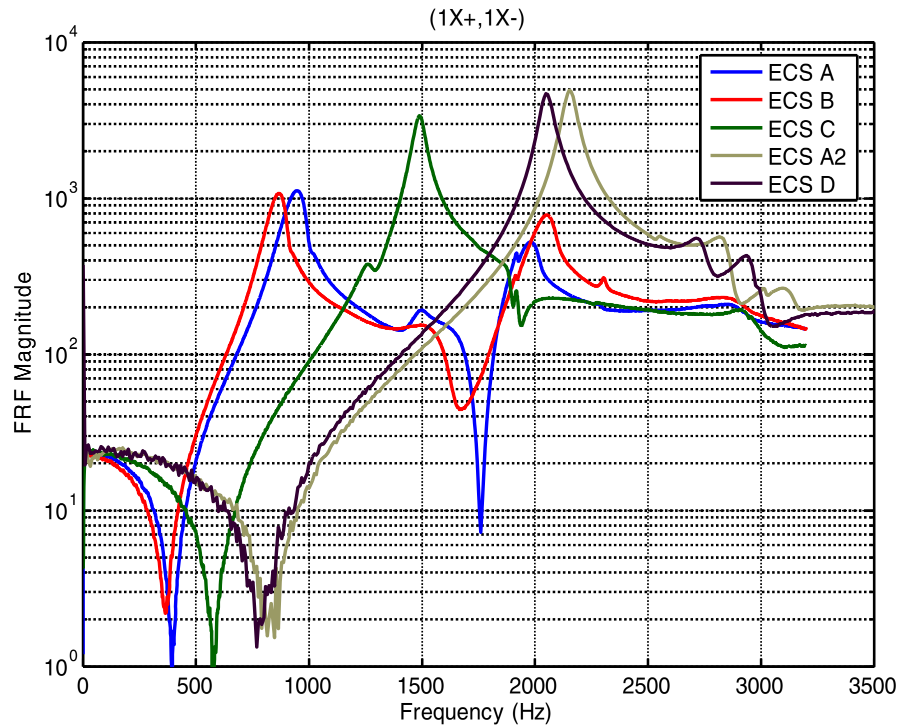


LFU Validation: New Samples

- LFU Foaming process reviewed
- Pre-foaming process included both grit blasting and Brulin®
- Two new validation samples created
- Parallel effort initiated to characterize non-bonding
- Time constraints required success-driven approach

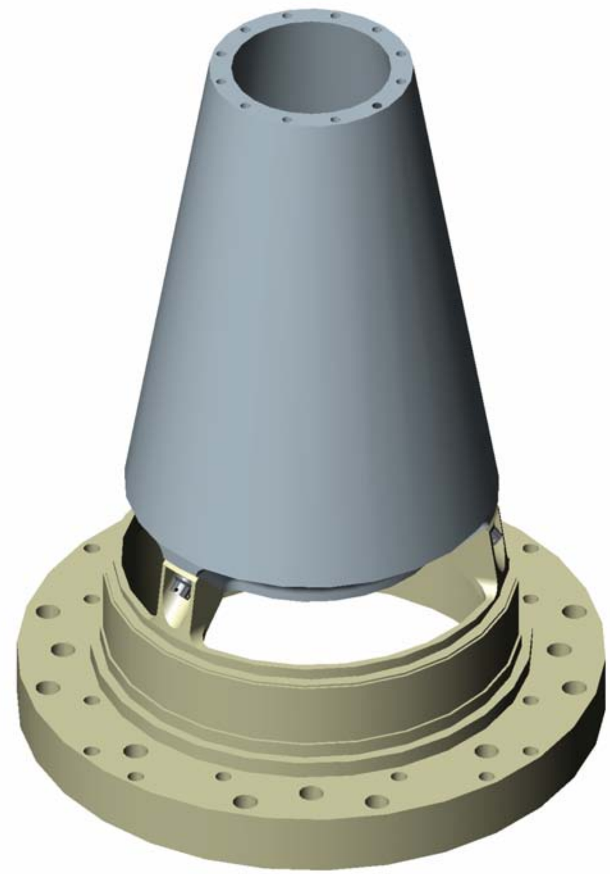
LFU Validation: Model Valid. Data (revisited)

- Free-free modal test repeated
- FRF results for A2, D
  - more linear
  - increased stiffness
  - closer model agreement
- Pure axial motion mode shapes
- Complete set of data collected for validation



LFU Validation: Model Validation

- Validation metrics applied to experimental data
  - harmonic wavelet transform of impulse response function
  - windowed measure of FRF
  - SRS measure
- Validation agreed on 2/3
- Agreement information defines adequacy of model
- Details will be documented in future paper

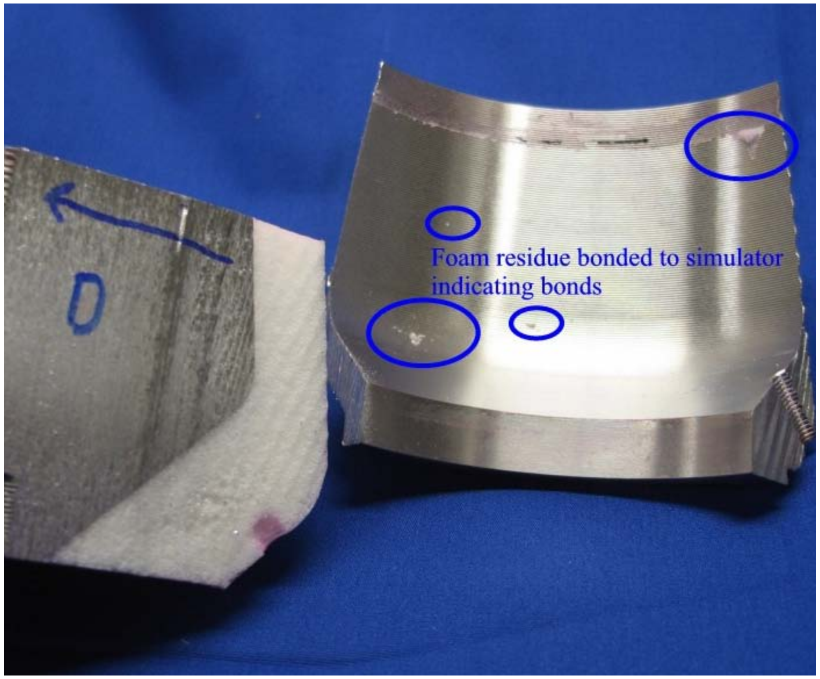


Summary

- An FEA model of Experimental Hardware was developed, incorporating encapsulated components in a linear viscoelastic foam
- Validation performed at Material → Subsystem levels
- Inconsistent, non-linear behavior in subsystem tests resulted in a new foaming procedure with better results
- Triple-blind validation process was based on a series of foam/structure experiments with increasing complexity
- Acceptance information helps define the adequacy of the model for the intended application

Summary: Lessons Learned

- Fully consider modeling assumptions
- Reassess at each level in validation process
- Previous experience indicated bonding would not be an issue
- Unclear why bonding did not occur in LFU
- Further investigation is being conducted



Model Assumptions may be violated (reality ≠ design)