SAND2006-3636C

Development and Validation of a Viscoelastic Foam Model for Encapsulated Components

Society of Experimental Mechanics Conference, St. Louis
June 5, 2006

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Overview

- Introduction
- Viscoelastic Model Description
- Model Parameter Identification with UQ
- Model Predictions compared to Test Data
- Conclusions
- Future Work

Foam Model Development and Validation Team

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Foam Development
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Foam Development
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Viscoelastic Modeling
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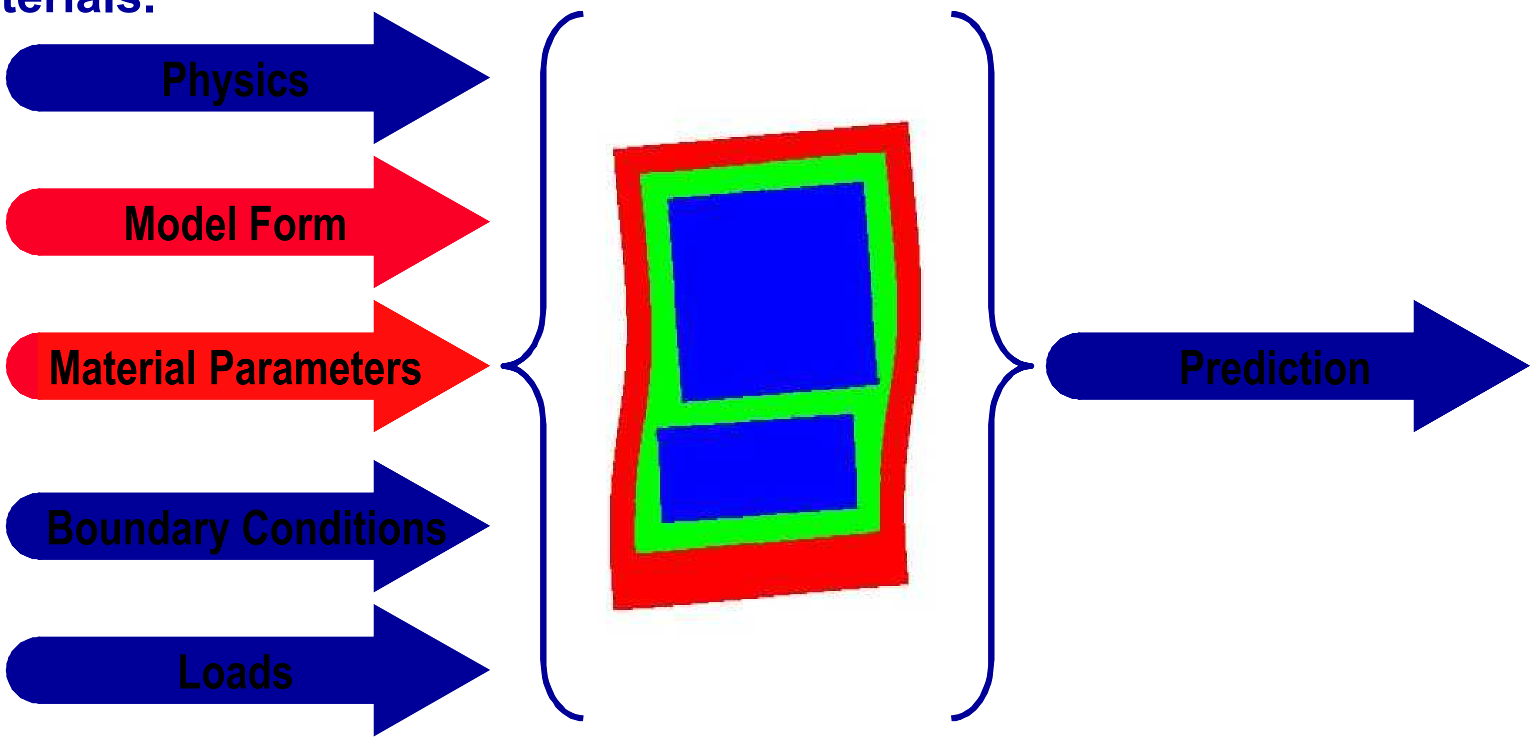
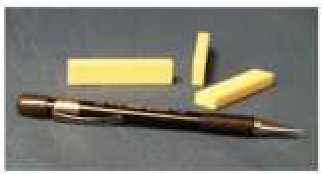
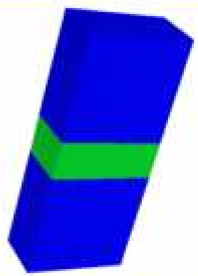
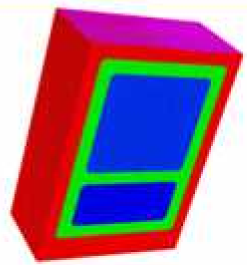
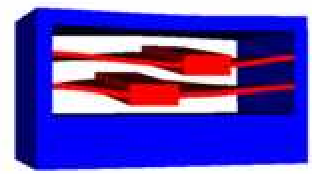
Viscoelastic Modeling

Project Objective

The objective of this project is to improve the predictive modeling capability of components and systems using foam encapsulants. Specifically, this project seeks to support the development, calibration and validation of finite element models using foam encapsulant materials.



Foam/Component Development Process

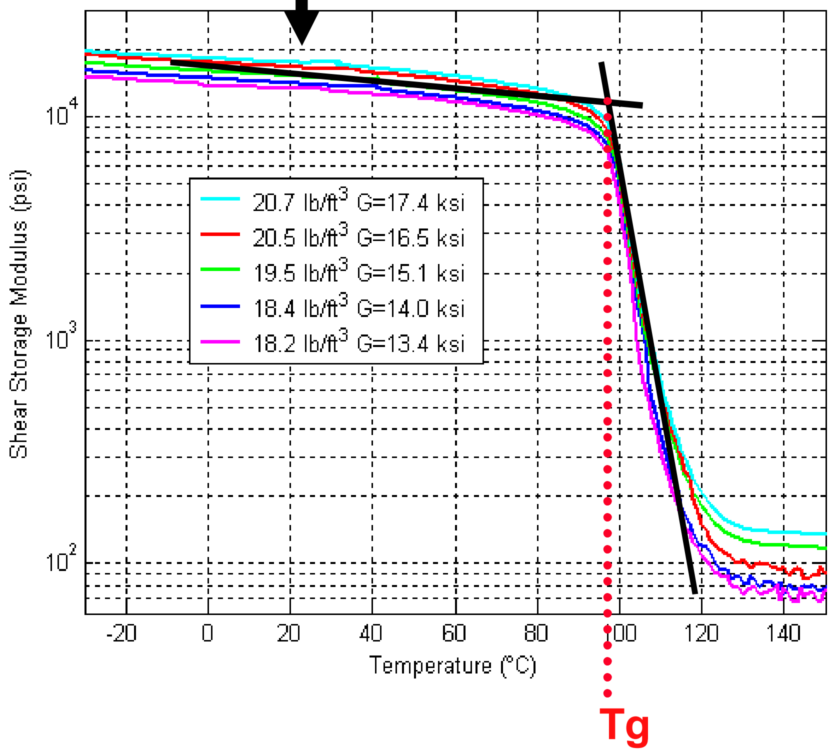
Material/Component Validation		Benchmark Validation		Subsystem Validation
Phase 0	Phase I	Phase II	Phase III	LFU
				
Constitutive	Dumbbell	Rigid Component	Flexible Comp.	Subsystem Mock

INCREASED COMPLEXITY

- Project experiments will emphasize the fundamental physics associated of foam-confined components with geometries of increased complexity
- The physical parameter space is significantly simplified, but the **environmental parameter space** involving temperature, frequency, strain and density **will be maintained**

Goal of Viscoelastic Model Development

Room Temperature is approx. 70 deg below Tg



Will not be using Proportional Damping that adds unwanted damping throughout the structure

Goal of Viscoelastic Model Development: Accurately represent the elasticity and predict the small amount of damping that is present in the foam at room temperature

Calibration Procedure for the Viscoelatic Model in the Salinas Code

Dynamic Mechanical Analysis (DMA) Tests provides:

- estimates trend of shear modulus vs. frequency and temperature
- basis for fitting Prony Series
- estimates of material loss factor
- still need second elastic constant
- works best near the glass transition temperature (95 deg C)

Phase I Modal Tests

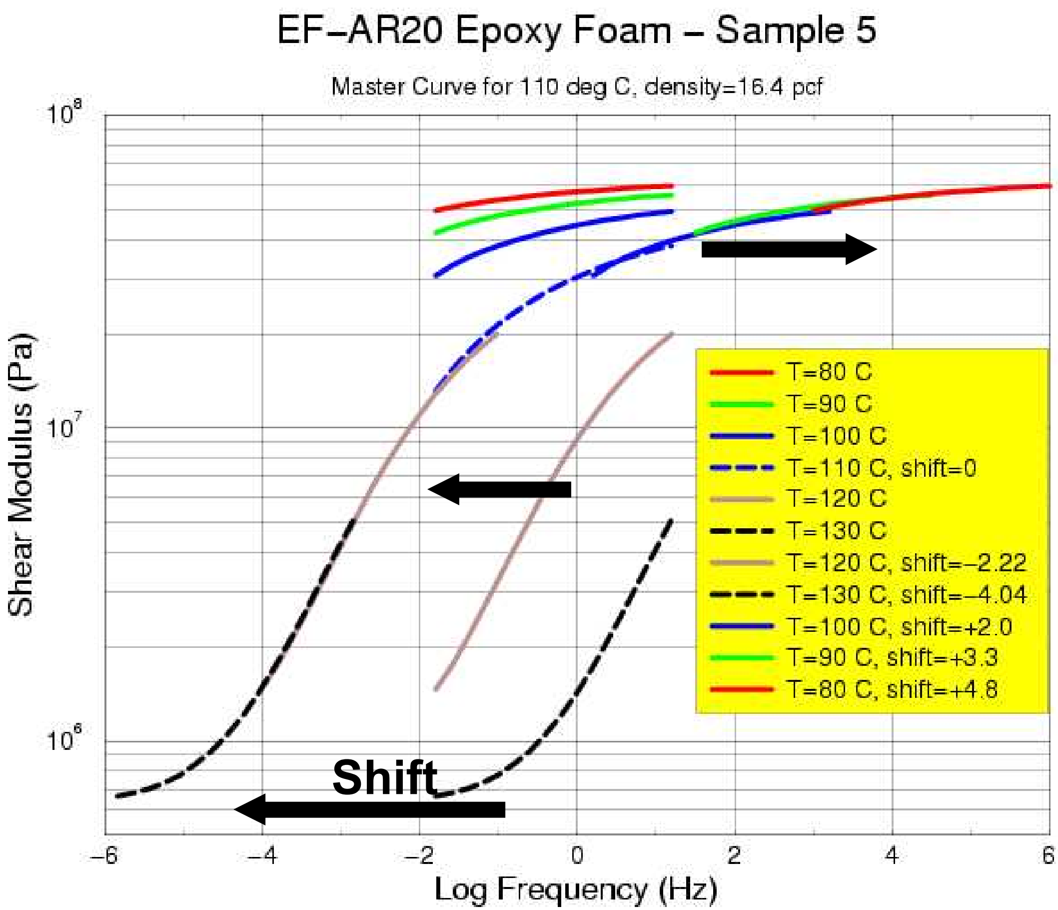
- provides modal frequencies and damping
- analytically back out E and G with Salinas by matching test modes

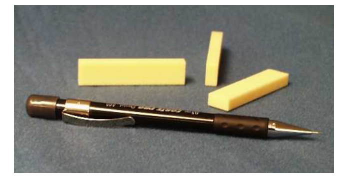
Prony Series

Viscoelastic Model

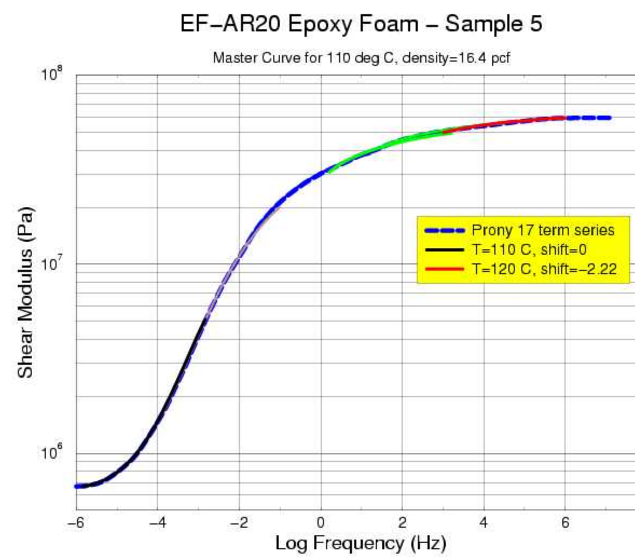
Young's Modulus, Shear Modulus and damping

Constitutive Experiments
DMA Temperature/Frequency Shifts

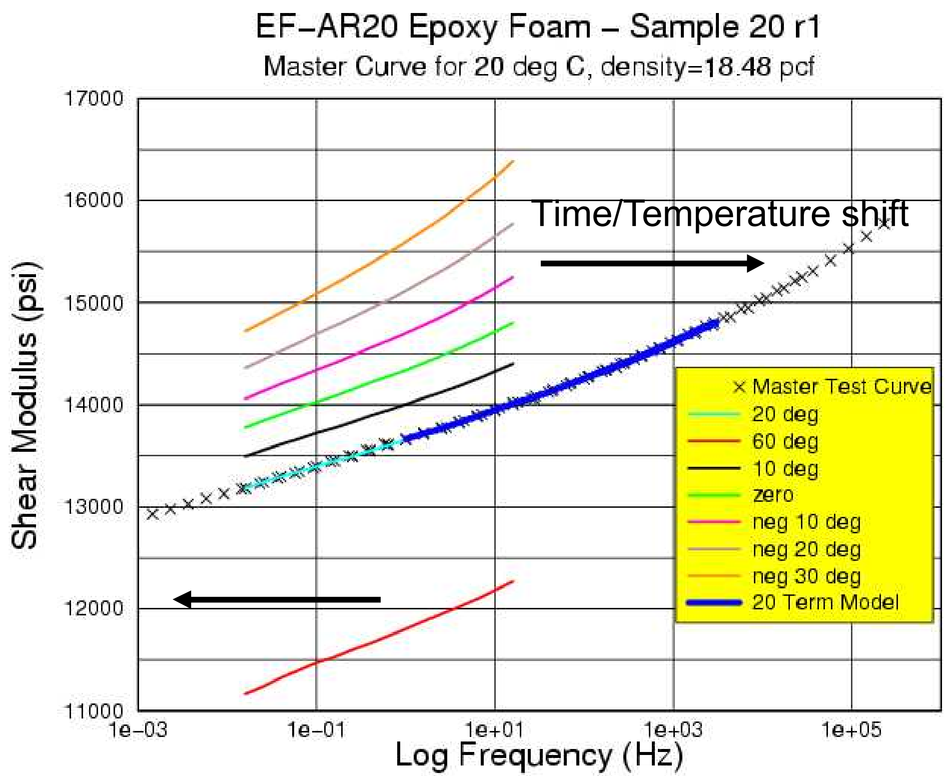




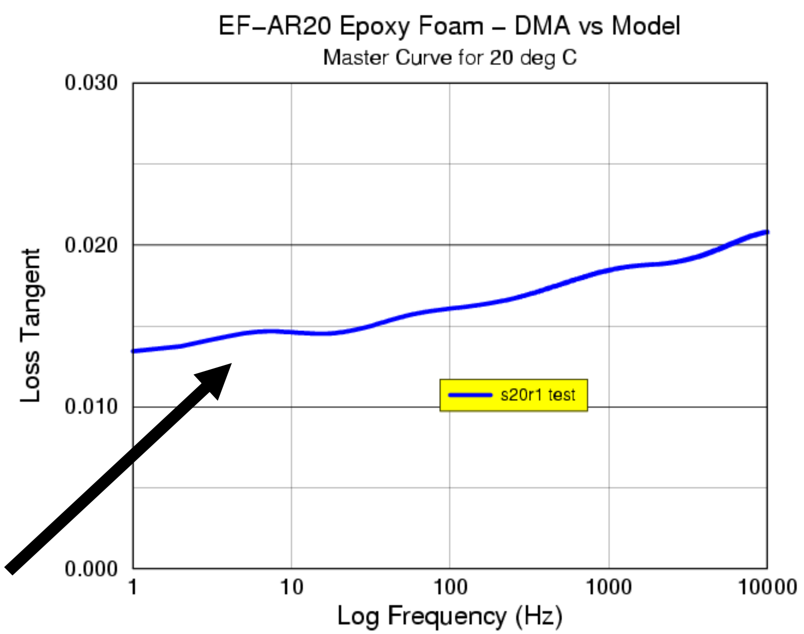
17 Term Prony Series Fit



Prony Model of Master Curve at Room Temperature

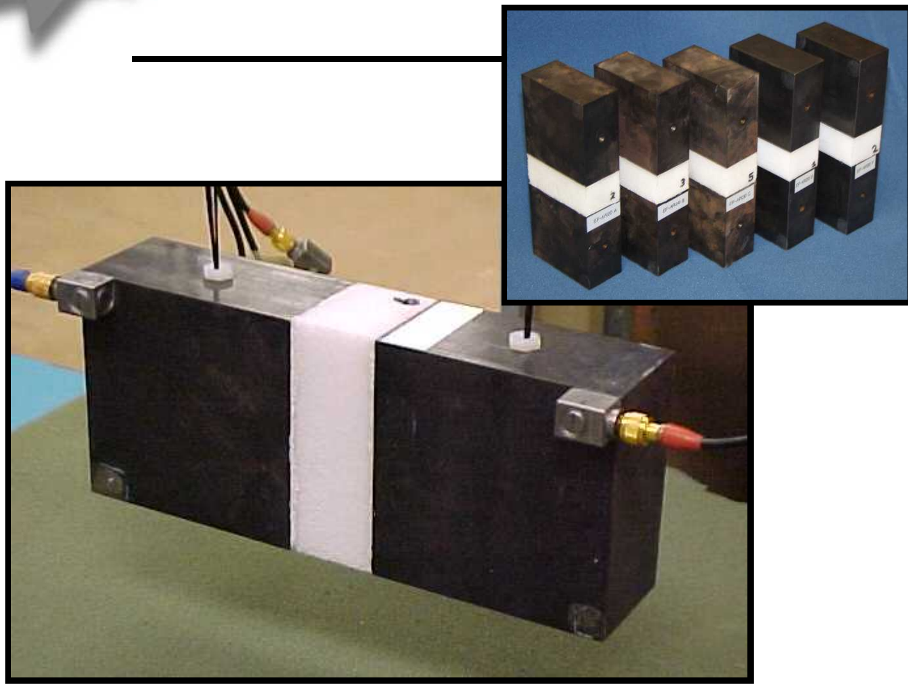


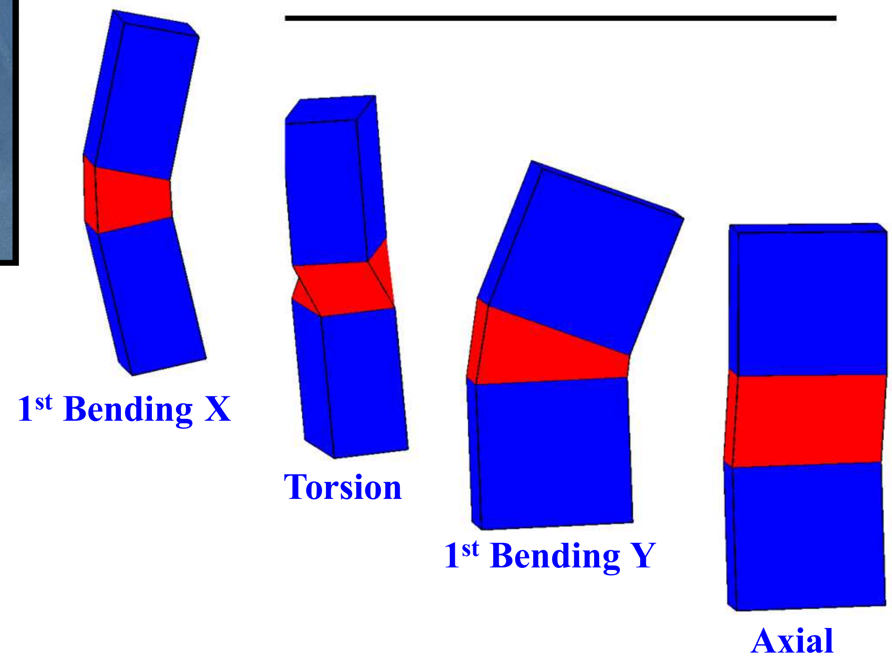
- Individual DMA curves shifted to form Master Curve
- 20 Term Prony Series fit to Master Curve (blue curve)



Resulting master curve for Loss Tangent (damping = 0.5 LT for Phase I)

EF-AR20 Phase I Calibration Data

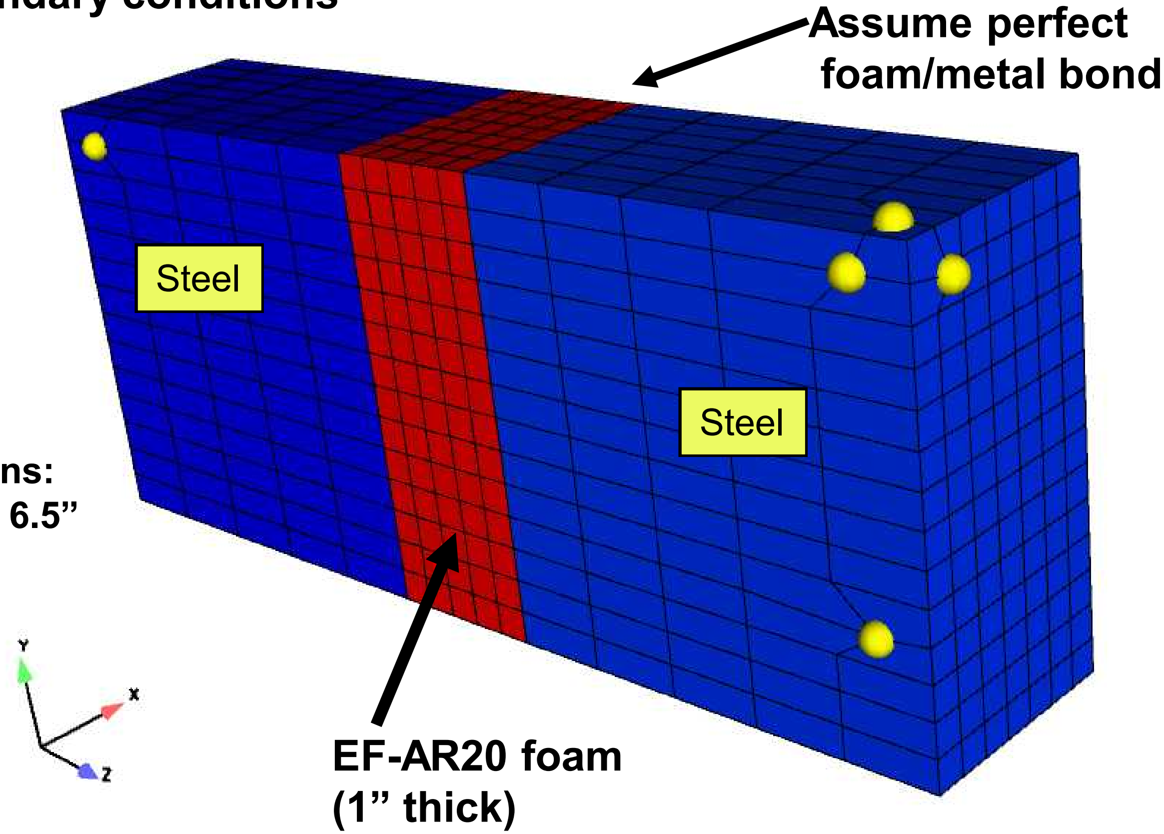




- Phase I samples used to supplement constitutive data
- Mechanism to test various frequencies at room temperature
- Low strain helps minimize uncertainties caused by cellular interaction
- 27 Phase I baseline samples
- 6 Phase I Calibration samples
- 5 Phase I Validation samples

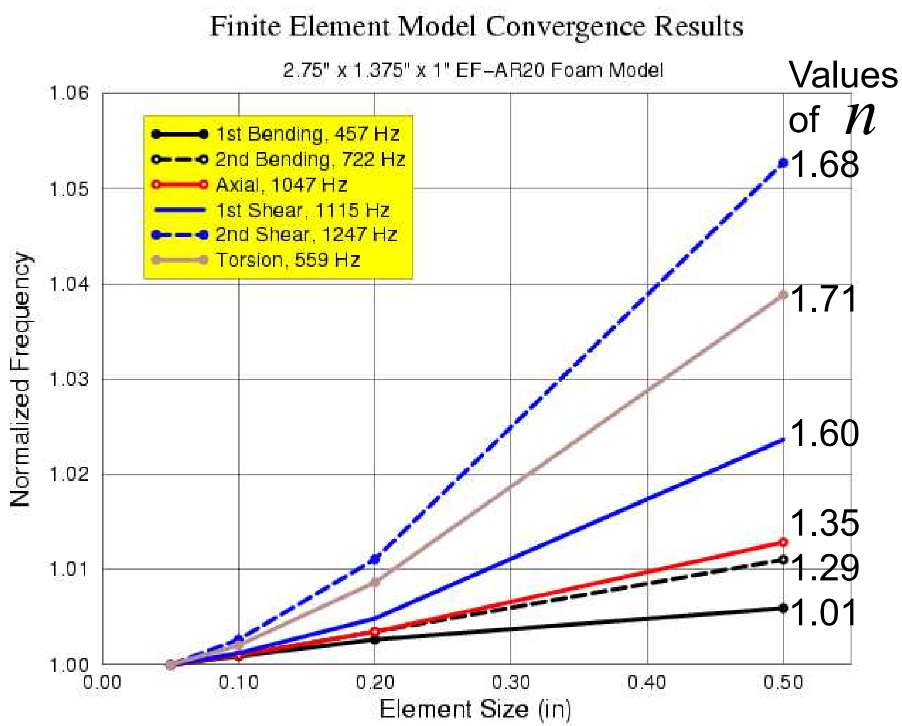
Phase I Calibration Finite Element Model

- 1470 eight node hex elements
- 1920 nodes
- yellow spheres designate input/output node set locations
- free-free boundary conditions

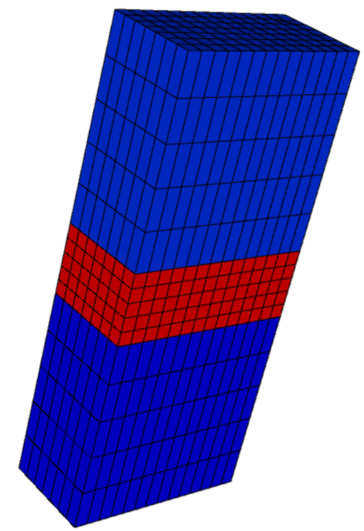


Outer Dimensions:
1.375” x 2.75” x 6.5”

Phase 1 Model Convergence using Modal Frequencies



0.2" element selected for computational efficiency



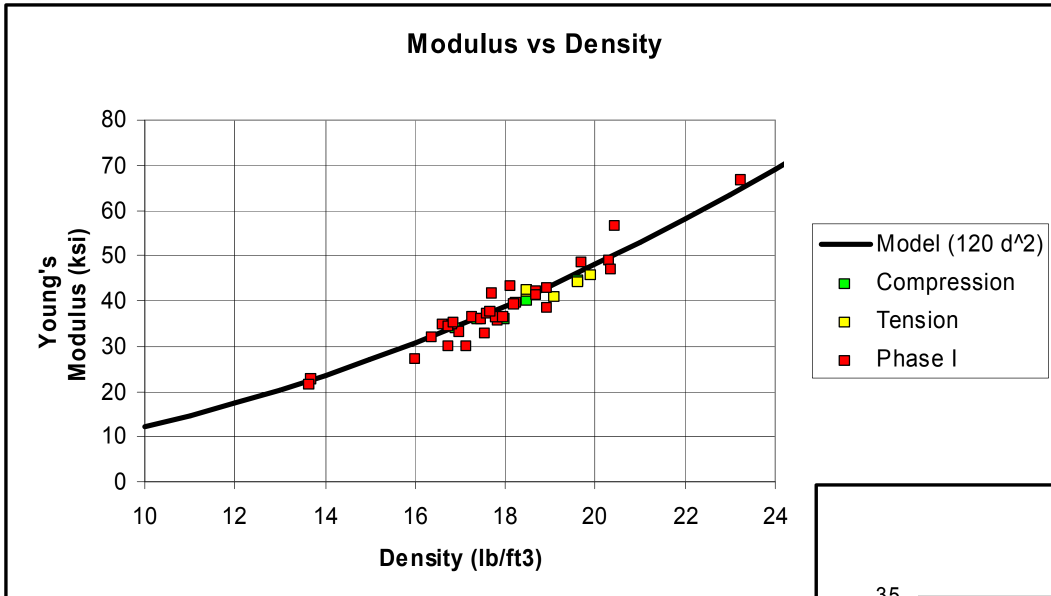
8 node hexahedral elements used

Richardson Extrapolation: $E(h) = E' + Ch^n$

Exponent n, has values given above, ranging from 1.01 to 1.71

Normalized error, $(E - E')/E'$, same as shown in plot at h = 0.2, **less than 1.3% error**

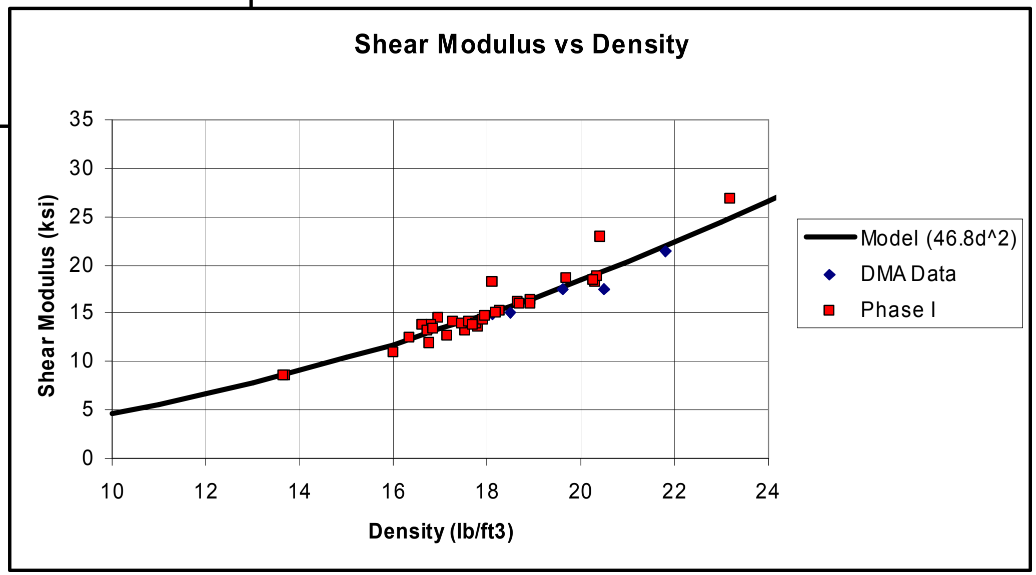
Experimental/Analytical Estimating Results for EF-AR20 Modulus vs Density



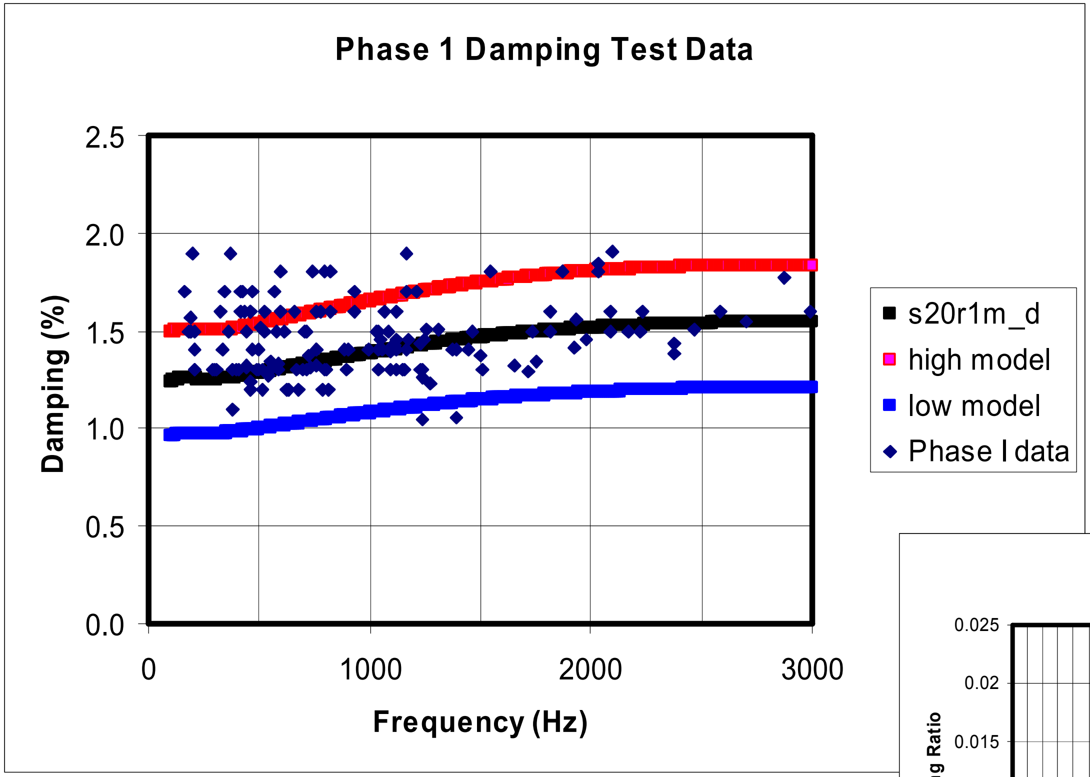
- Plot of experimentally inferred Young's and Shear modulus as a function of density (dots)
- Perform regression to estimate parameter of squared function fit
- Correlation of E and G residuals will be matched also

- **Modulus proportional to density squared**
- **Results compare well with models from Gibson & Ashby's "Cellular Solids:**

$$E = E_s \left(\frac{\rho}{\rho_s} \right)^2$$

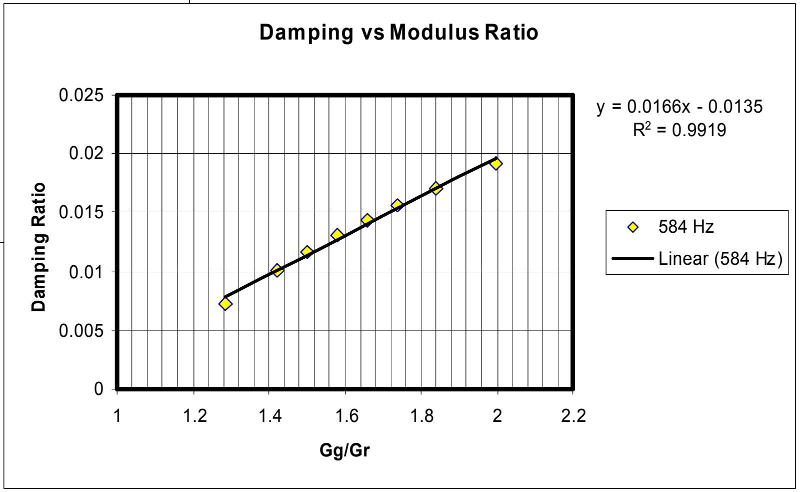


Phase I Exerimental Damping versus Viscoelastic Model Damping

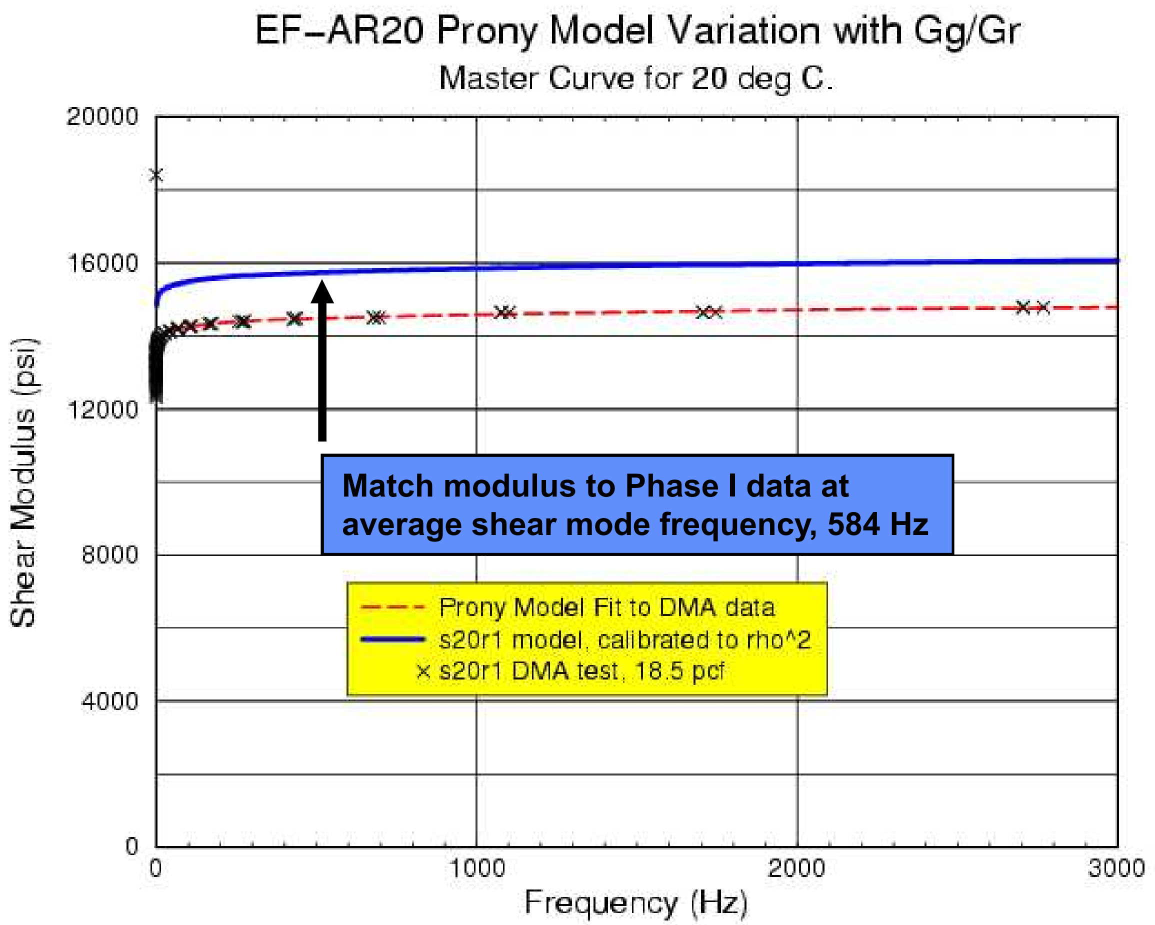


Will treat damping as a random variable

- Three Prony series realizations shown with colored curves
- damping will be specified via modulus ratios as shown below

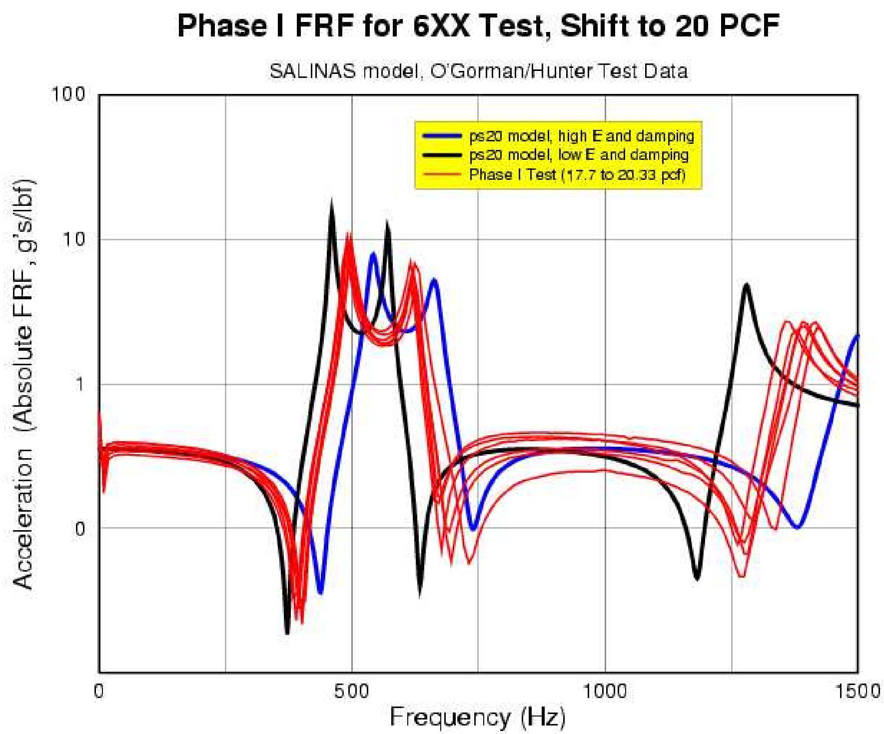


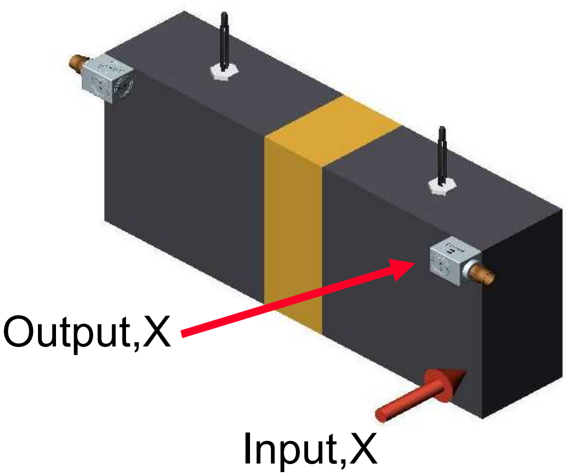
Matching Prony Series Model with Phase I Test



Prony Series model is matched to Phase I derived modulus values by shifting the curve with modified Gg and Gr values

SALINAS Viscoelastic Model Predictions of Phase I Calibration Tests with EF-AR20 Foam



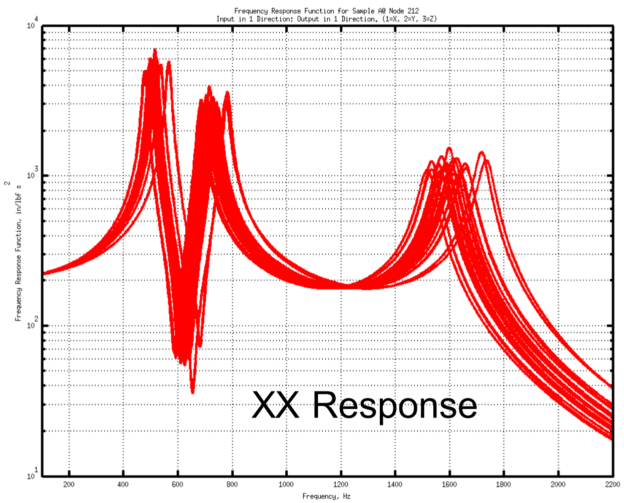


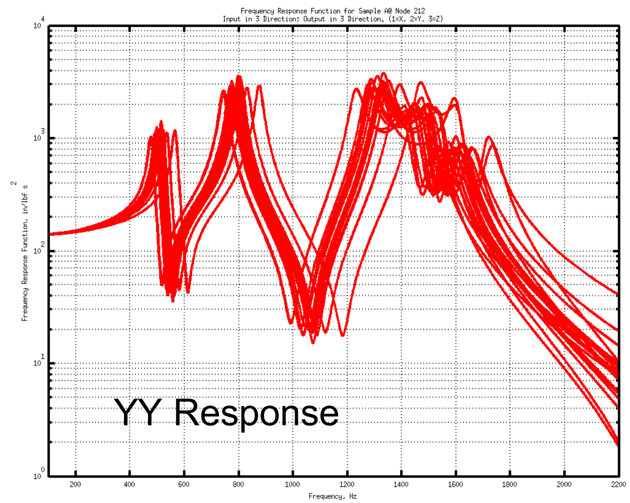
6 sets of test data shifted to common density of 20 pcf

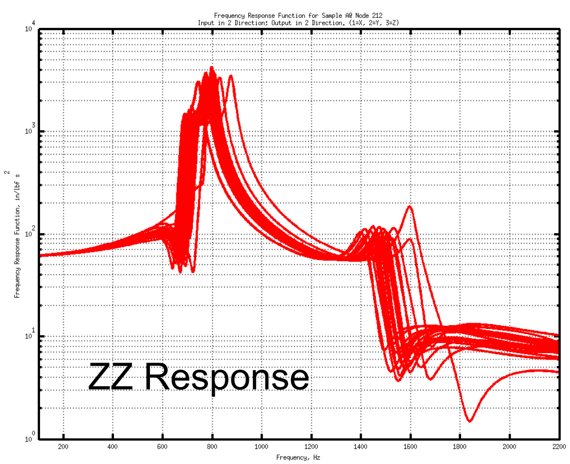
$$f_2 / f_1 = \sqrt{E_2 / E_1} = \rho_2 / \rho_1$$

Model brackets composite of test data between high modulus/damping and low modulus/damping predictions

Phase I Validation Model Predictions For Free-Free Conditions

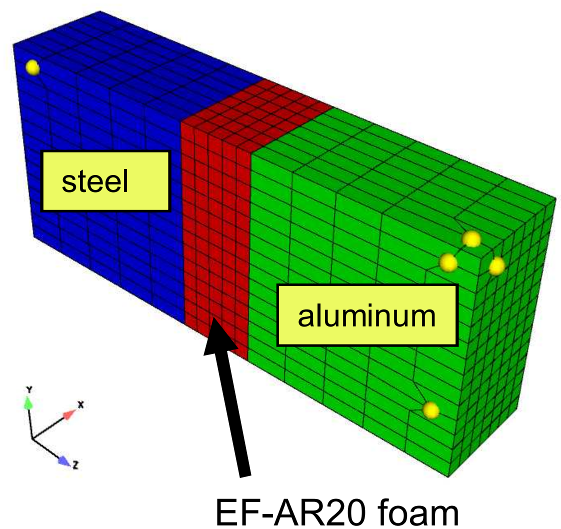






20 sets of random variables generated to represent PDF of:

- E -Young's Modulus
- G - Shear Modulus
- Density
- Damping

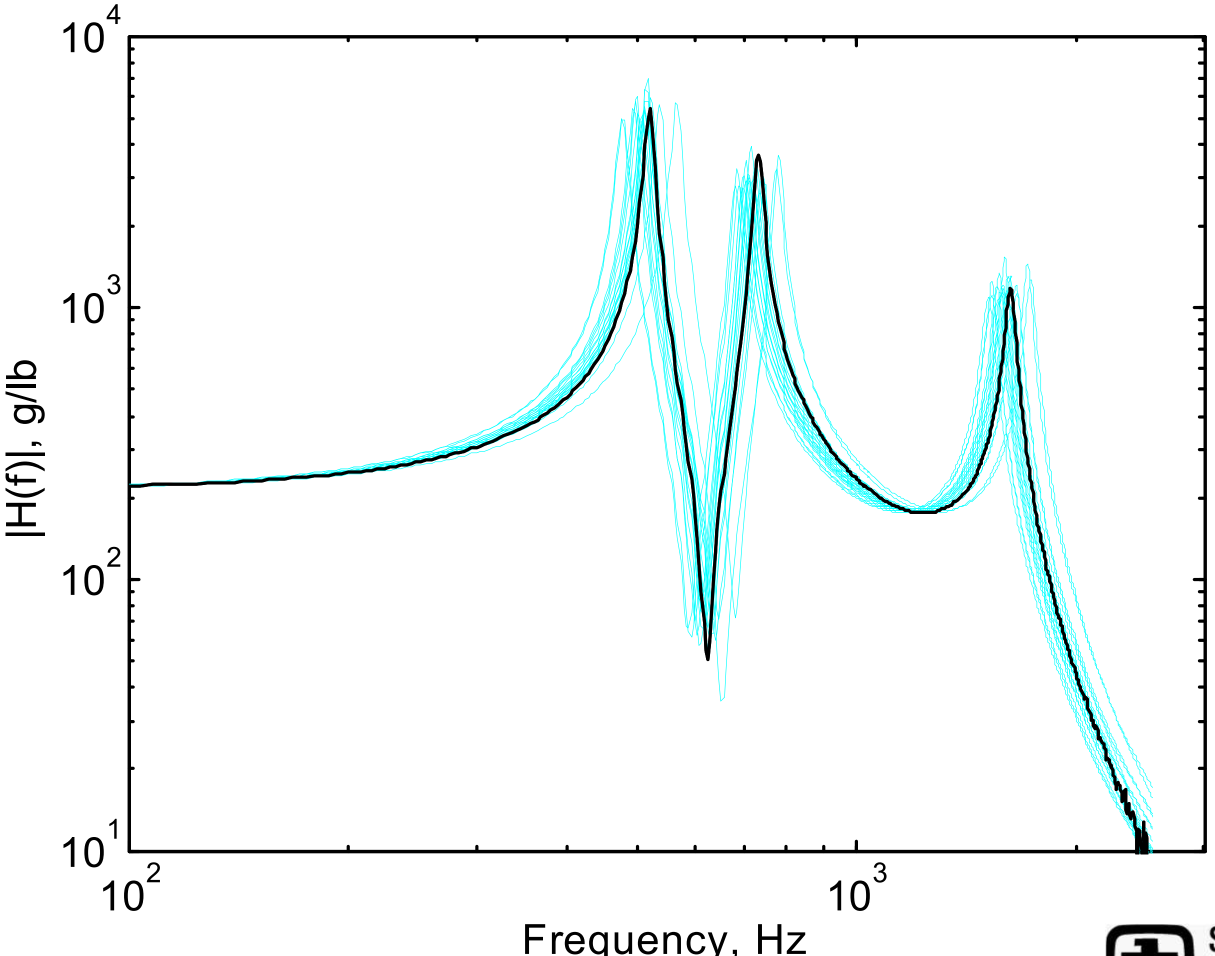


Phase I Experiment/Model Prediction

x – direction, ρ = 16.42 lb/ft^3

Experiment
- One realization
- At each of five densities
- Tested in three directions

Model
- 20 Realizations
- At each of the five densities
- Predicted in three directions



Summary & Conclusions
Foam/Component Mechanical Modeling

- Model convergence adequacy demonstrated
- Salinas viscoelastic model parameters identifed
  - Fit Prony series to master shear modulus curve for room temperature based on DMA test data
  - Fine tuned viscoelastic model derived from DMA tests with modulus and damping measured in Phase I Tests
- Random variables modeled:
  - Young's and Shear modulus with correlation
  - Damping and Density
- Phase I model is calibrated and model validation predictions computed

FY06 Foam Modeling Plans

Viscoelastic Model Calibration & Validation Plans, FY06

	Phase 0		Phase 1		Phase 2		Phase 3	
Material	Ambient	L/H Temp	Ambient	L/H Temp	Ambient	L/H Temp	Ambient	L/H Temp
EF-AR20	C	C	V/C	V/C	V	V	V	V
REF 308	C	C	V/C	V/C			V	V
REF 320	C	C	V/C	V/C				
RSF 320	C	C	V/C	V/C				
PMDI 20	C	C	V/C	V/C				
TF6070	C	C	V/C	V/C				

Backup Slides

- **Backup**
- **Slides**

Development Process

Model Development

- Evaluate the applicability of linear viscoelastic constitutive models for epoxy foams used as potting material in weapon systems
- Code verification for linear viscoelastic materials

Calibration

- Identification of model parameters through a series of constitutive tests which include quantification of parameter uncertainties

Validation

- Using models incorporating parameters from calibration experiments to make response predictions for validation experiments

Linear Viscoelasticity in SALINAS

- **Stress is an Integral function of strain: Convolution Integral**

$$\sigma_{ij}(t) = \int_0^t \widehat{G}_{ijkl}(t-s)\frac{d\varepsilon_{kl}}{ds}ds$$

- **Isotropy is assumed:**

$$\sigma_{ij}(t) = \int_0^t 2G(t-s)\frac{d}{ds}\varepsilon_{ij}^d\, ds + \delta_{ij}\int_0^t K(t-s)\frac{d}{ds}tr(\varepsilon)\,ds$$

where $\varepsilon^d = \varepsilon - \delta_{ij} tr(\varepsilon)/3$

- **Material functions** $G(\ )$ **and** $K(\ )$ **are selected to reproduce experimental data**

Model Form in SALINAS Code

Measure Shear Relaxation Modulus with DMA tests and fit Prony Series:

$$G(t) = G_r + (G_g - G_r)\sum_{j=1}^{N} m_j \exp(-t/\tau_j)$$

Use same Prony Series for the Bulk modulus and estimate K_g and K_r:

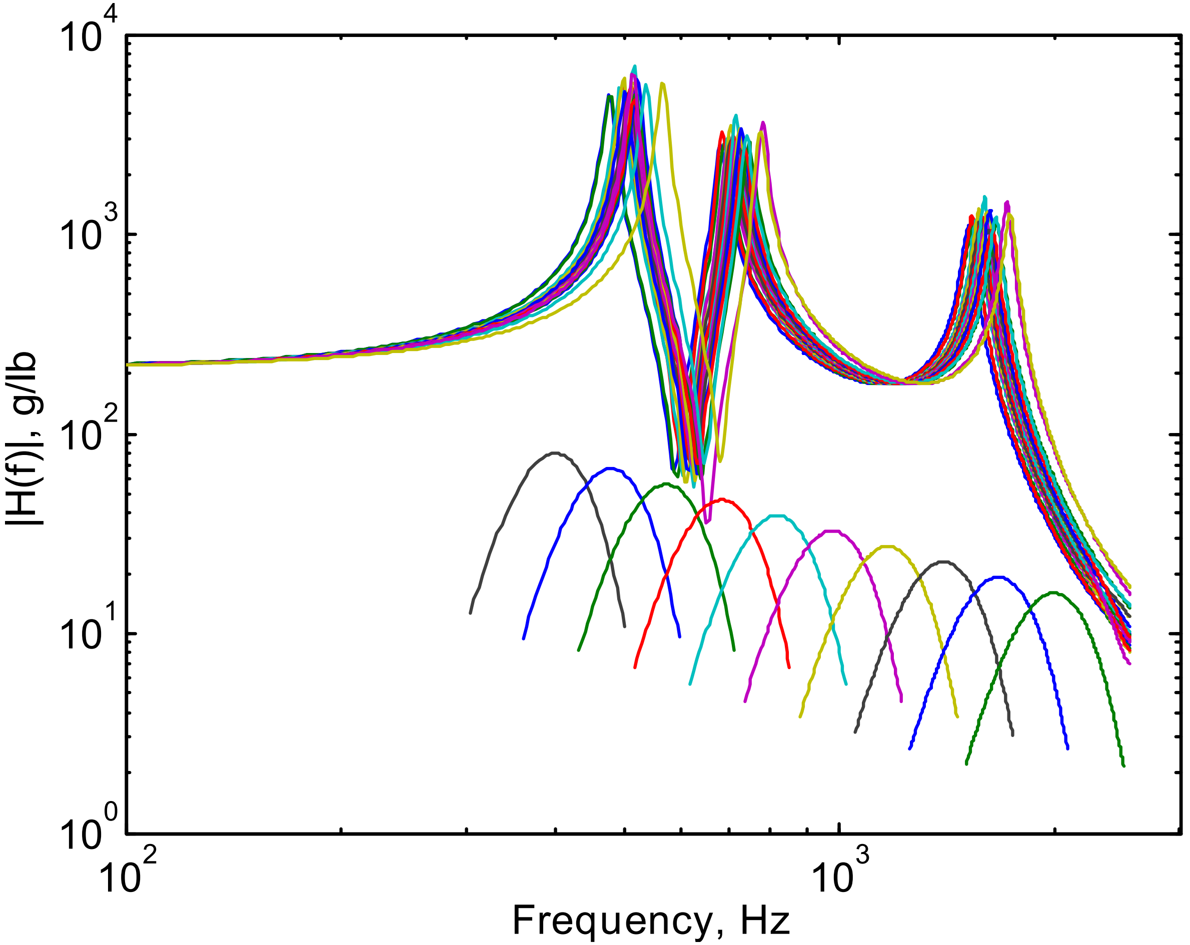
$$K(t) = K_r + (K_g - K_r)\sum_{j=1}^{N} m_j \exp(-t/\tau_j)$$

A constant value of Poisson's ratio with UQ for this viscoelastic foam will be used based on best estimates from measuring E and G directly in constitutive tests and indirectly from Phase I modal tests.

Assuming Isotropic behavior, Poisson's Ratio is: $\nu = (\frac{E}{2G}) - 1$

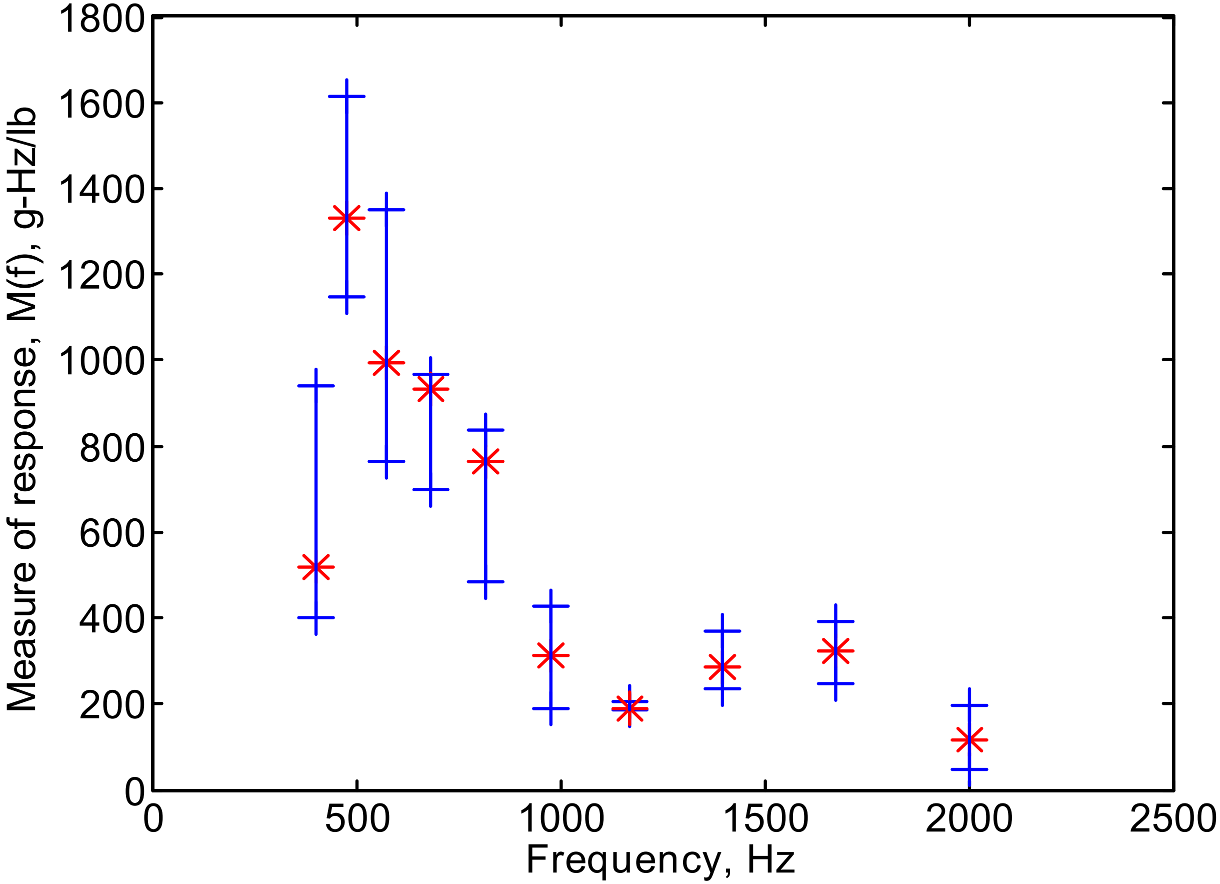
and the Bulk Modulus will be estimated as follows: $K = 2G(1+\nu)/3(1-2\nu)$

Window Functions for Validation Metric



Example

Phase I Validation Specimen, 16.42 lb/ft^3, x – direction, 90% prob intervals [L_{90},U_{90}] of $M_{mod}(f_c)$ and $M_{exp}(f_c)$

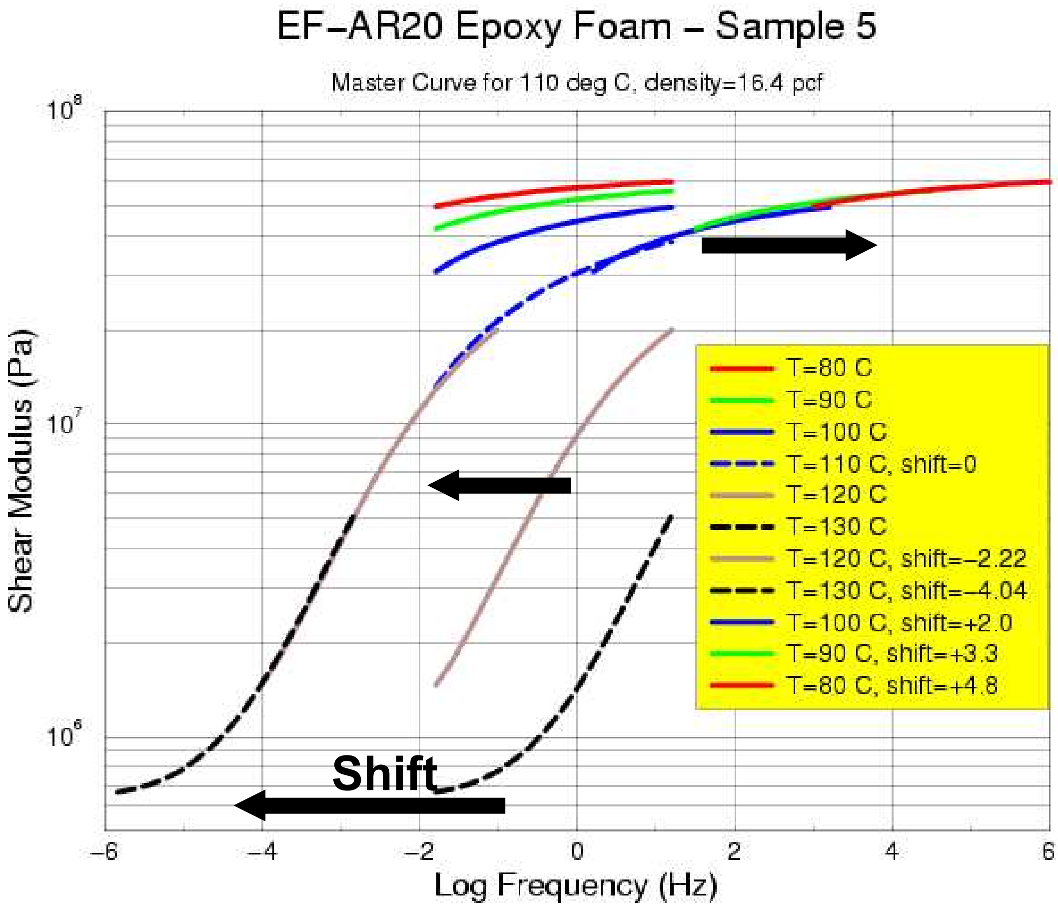


Foam Model Applicability

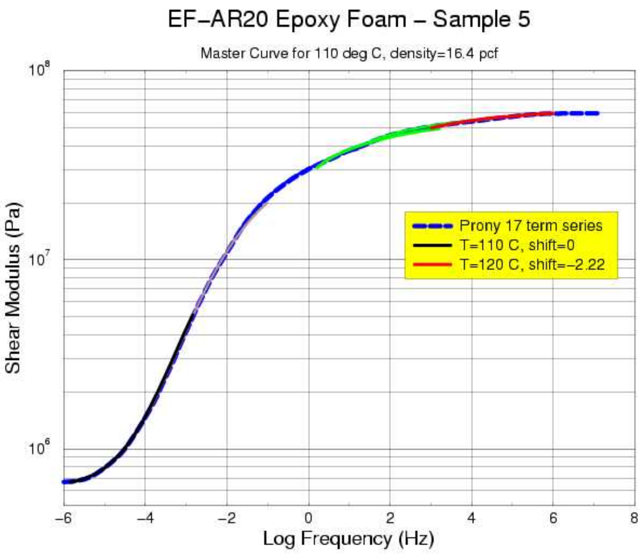
- Stochastic form of foam model suitable for simulation of some measures of response of EF-AR20 foam under some environments at room temperature
- Foam model calibrated via modal analysis and finite element model parameter identification, and validated for hammer impact/decaying response to produce adequate frequency response function predictions in the frequency range [400,2000] Hz, at strain levels up to 0.05 percent
- Model parameters determined throughout density range [14,22] lb/ft^3 and suitable for hostile blast level predictions within that range for strains up to 0.05 percent
- No significant evidence found to reject inferrence that visco-elastic model functions correctly in Salinas code
- Phase I validation success indicates the visco-elastic material model is satisfactorily credible and encourages progressing to next level of validation complexity

Constitutive Experiments

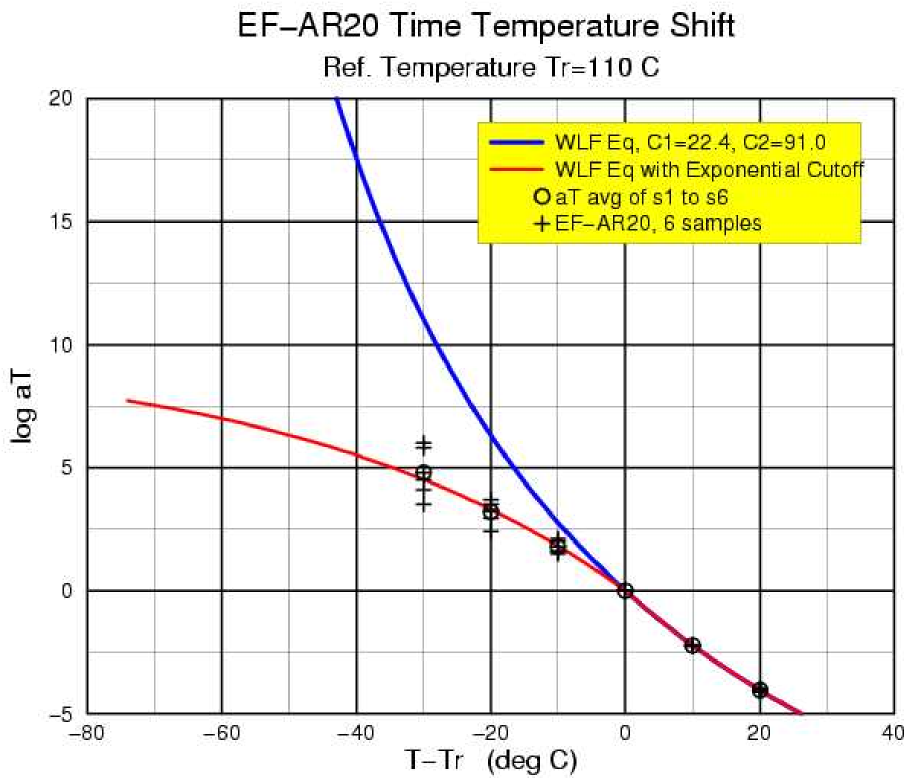
DMA Temperature/Frequency Shifts



17 Term Prony Series Fit



Time(Frequency)/Temperature Shift Function based on the Master Curve for EF-AR20 Foam



Time domain:

$$G(t) = G_r + (G_g - G_r)\sum_{j=1}^{N} m_j \exp(-t / a_T\tau_j)$$

Frequency domain:

$$G'(\omega) = G_r + (G_g - G_r)\sum_{j=1}^{N} \frac{m_j(\omega a_T\tau_j)^2}{(1+(\omega a_T\tau_j)^2)}$$

where:

$$a_T = t / t_r$$

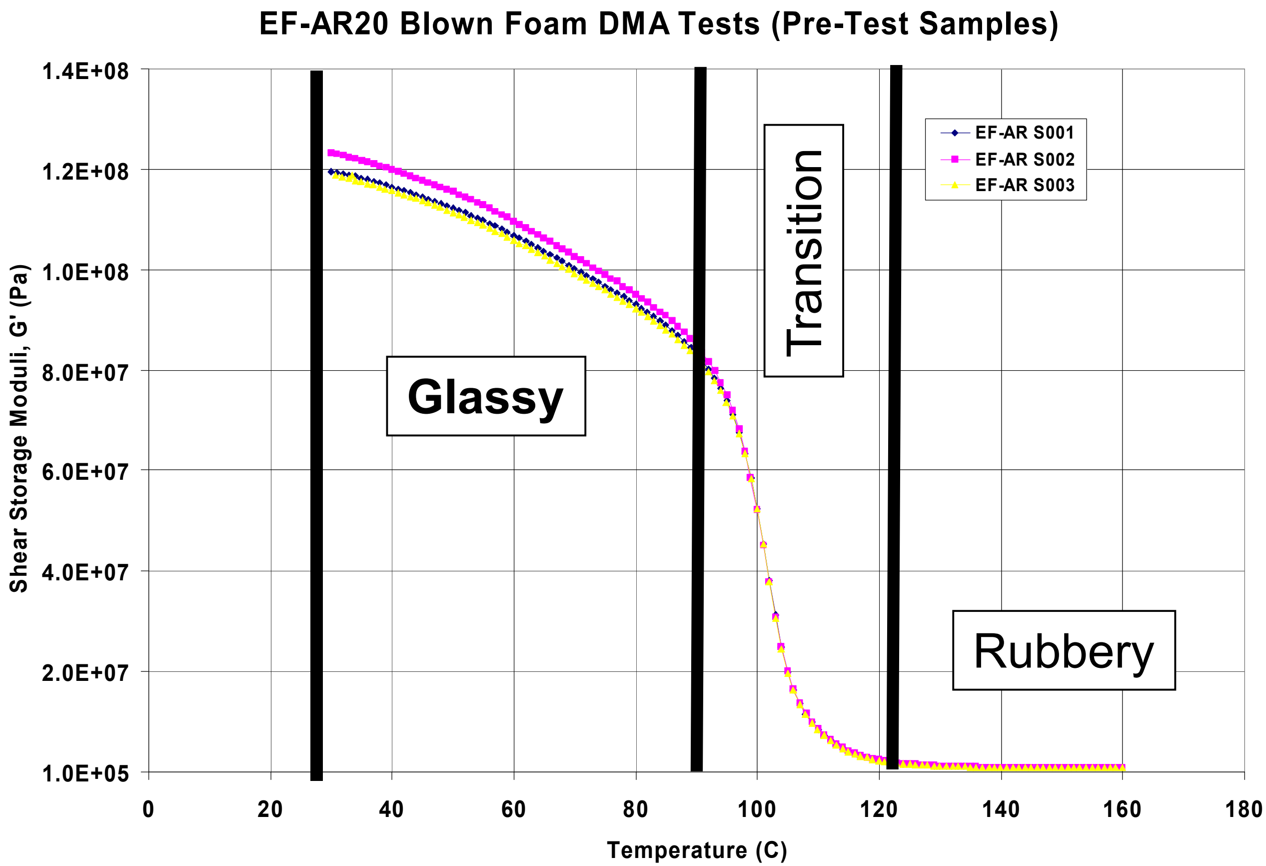
t_r = **reference time**

Modified WLF Time-Temperature Shift Function

$$Log(t/t_r) = (-C_1 * (T - T_r)) / (C_2 + (T - T_r)) \qquad T > T_r$$

$$Log(t/t_r) = a_1 * (1 - \exp(a_2 * (T - T_r))) \qquad T < T_r$$

Glassy Modulus depends on Temperature

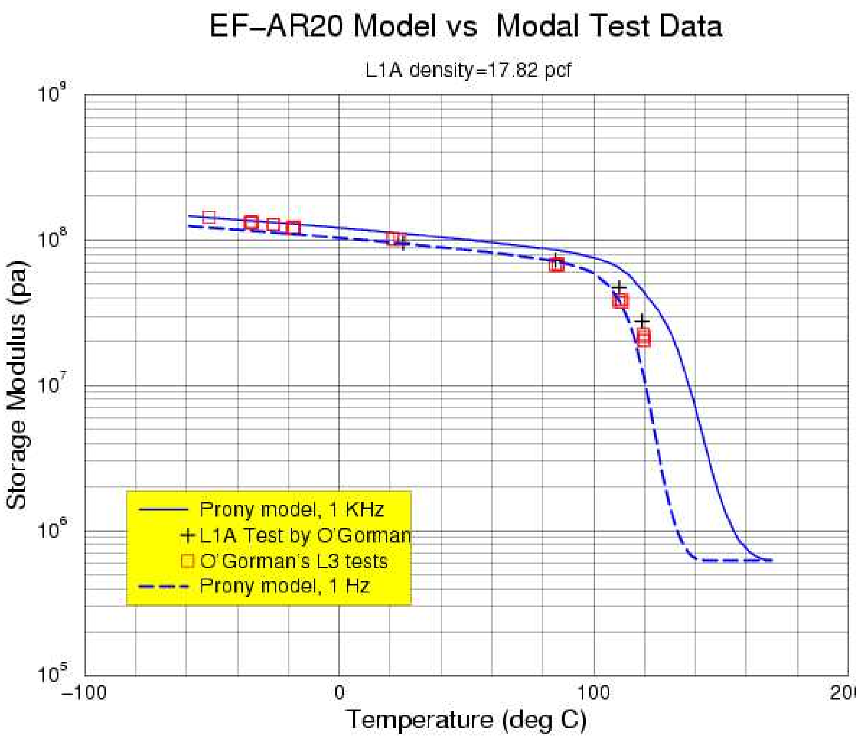


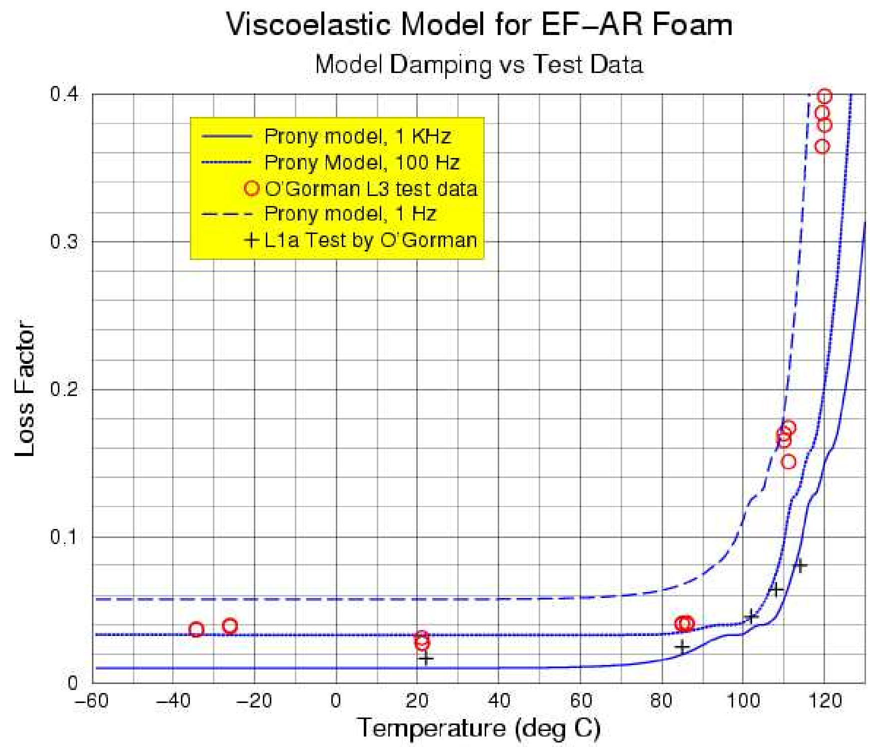
Glassy modulus has an approx. linear temperature dependence in the Glassy region that can be combined with the Prony series model as shown below

$$G_g = G_{g@Tg} * A_1 * (1 - A_2 * T / T_g)$$

Epoxy Foam Behavior

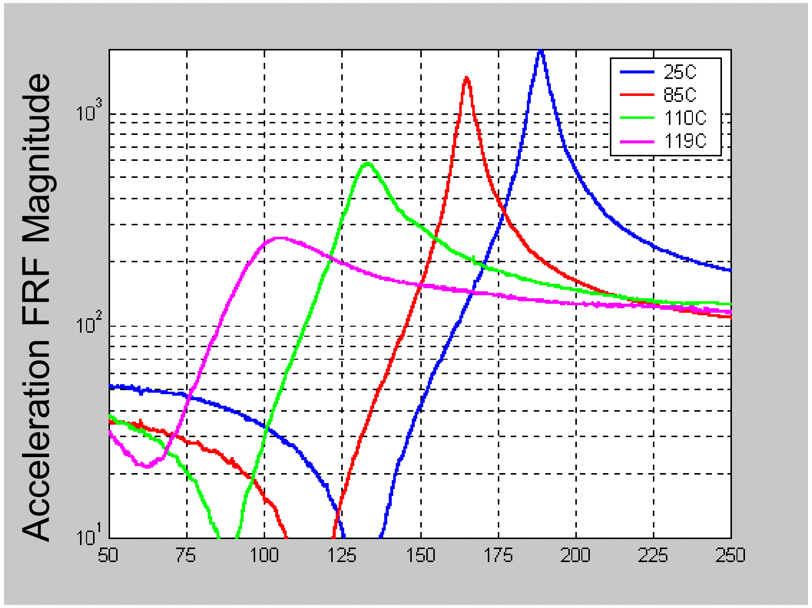
Modulus & Damping vs Temperature
Test Data superimposed on model curves





Modal Test Results Compared with SALINAS Viscoelastic Model

Modal Test Data
ref. O'Gorman



SALINAS Model Results
ref. Hinnerichs