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Validation of a Viscoelastic Model for Foam Encapsulated Component Response Over a Wide Temperature Range

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ABSTRACT

Accurate material models are fundamental to predictive structural finite element models. Because potting foams are routinely used to mitigate shock and vibration of encapsulated components in electro/mechanical systems, accurate material models of foams are needed. A linear-viscoelastic foam constitutive model has been developed to represent the foam's stiffness and damping throughout an application space defined by temperature, strain rate or frequency and strain level. Validation of this linear-viscoelastic model, which is integrated into the Salinas structural dynamics code, is being achieved by modeling and testing a series of structural geometries of increasing complexity that have been designed to ensure sensitivity to material parameters. Both experimental and analytical uncertainties are being quantified to ensure the fair assessment of model validity. Quantitative model validation metrics are being developed to provide a means of comparison for analytical model predictions to observations made in the experiments. This paper is one of several recent papers documenting the validation process for simple to complex structures with foam encapsulated components. This paper specifically focuses on model validation over a wide temperature range and using a simple dumbbell structure for modal testing and simulation. Material variations of density and modulus have been included. A double blind validation process is described that brings together test data with model predictions.

Nomenclature

aT – shift factor
c1, c2 – coefficients of the WLF equation
^{o}C – temperature in degrees Celsius
lbs - pounds
lbs/ft3 – pounds per cubic foot
b" – b inches
DMA – Dynamic Mechanical Analysis
E – Young's Modulus
F – cumulative distribution function
Gg – glassy shear modulus
Gr – rubbery shear modulus
G(T) – glassy shear modulus as function of temperature
G – shear modulus
ksi – 1000 pounds per square inch
m_j – Prony series coefficient
N – number of terms in the Prony series
P – probability
r – circle radius
S – scaler function of form density and the elastic modulus
t – time
t_R - reference time
T – test or simulated temperature in degrees Kelvin
Tg – glass transition temperature
WLF – Williams, Landel, Ferry equation
Z – standard normal random variable
z – normalized variates
α - regression coefficient for modulus as a function of density
ζ - damping ratio
θ - angle in radians
μ - mean deviation
ρ – density of the foam

σ_o - standard deviation for elastic modulus as a function of density
σ_ρ - standard deviation for material density
τ_j - Prony series time constant
ν - Poisson's ratio
χ_2 – Chi squared random variable with two degrees of freedom

Introduction

Structural foams are attractive for packaging sensitive components because they can support components and mitigate shock due to their low modulus and damping characteristics. Also, they have relatively low densities and can be used over a wide temperature band. Because potting foams are routinely used to mitigate shock and vibration of encapsulated components in electro/mechanical systems, accurate material models of foams are needed.

This paper will describe the calibration and validation of a linear-viscoelastic model for an epoxy foam referred to as EF-AR20 over an application space defined by temperature, strain rate or frequency and strain level. Both experimental and analytical uncertainties are being quantified to ensure the fair assessment of model validity. Quantitative model validation metrics are being developed to provide a means of comparison for analytical model predictions to observations made in the experiments. This paper is one of several recent papers [1-2] documenting the validation process for simple to complex structures with foam encapsulated components. The earlier papers described a linear viscoelastic model validation process for room temperature applications. This paper will specifically focus on model validation of a linear viscoelastic model for foam encapsulated component response over a wide temperature range. As before, material variations of density, modulus, and damping have been included. This linear-viscoelastic model is implemented in the Salinas structural dynamics code [4]. Also, a double blind validation process is described that brings together test data with model predictions. First the validation experiments will be described.

Validation Experiments

Epoxy foam referred to as EF-AR20 is a rigid structural foam. Its density is nominally 20 lbs/ft^3 but it has a substantial variation in density that will be discussed later. Blocks of this foam were fabricated and cut into shapes suitable for bonding into the test configuration.

A test configuration was chosen based on the ability to significantly exercise the foam during modal testing and be a relatively simple configuration for constructing, testing, and modeling. The dumbbell like structure met these criteria. As shown in Figure 1 it has two steel end blocks with the foam sample bonded between them. The size of the cross-section was 1.375" x 2.75", with the length of the foam (white block) and the steel blocks being 1.0" and 2.75", respectively. The weight of the steel blocks is 2.95 lbs. The non-square cross section was chosen to avoid symmetric modes in bending and shear and thus provide more resonant peaks in the frequency band of interest.

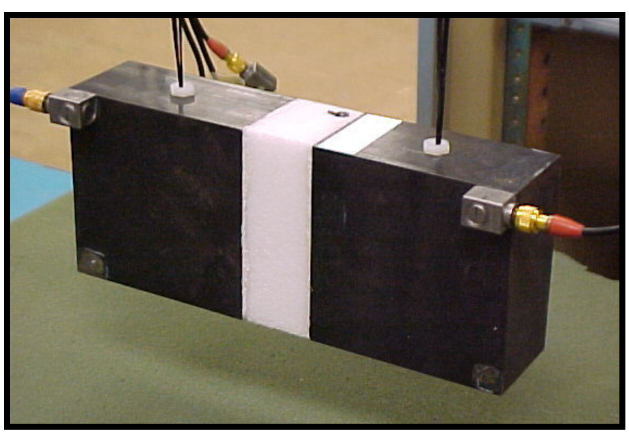

Figure 1. Photograph of the dumbbell test article with accelerometers and bungee cord supports.

Each sample was instrumented with two Endevco 65-10 triaxial accelerometers. The accelerometers were placed on the upper corners of each steel block.

Modal tests were performed on each of the samples at each of the temperatures shown in Figure 2.

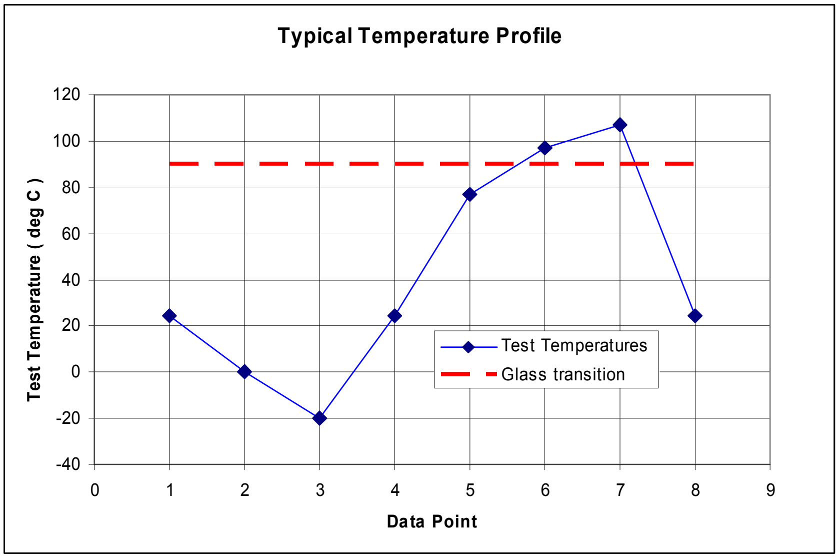

Figure 2. Typical temperature profile for modal testing.

These temperature set points were chosen to span the temperature range of interest and to have enough points to capture the transition behavior between rubbery to glassy behaviors. Also, ambient tests were performed before and after the cold and hot temperature excursions to measure any change in the foam properties.

The sample was suspended from a support structure using bungee cords in order to approximate a free-free boundary condition. The sample and support structure were placed in a climatic chamber as shown in Figure 3.

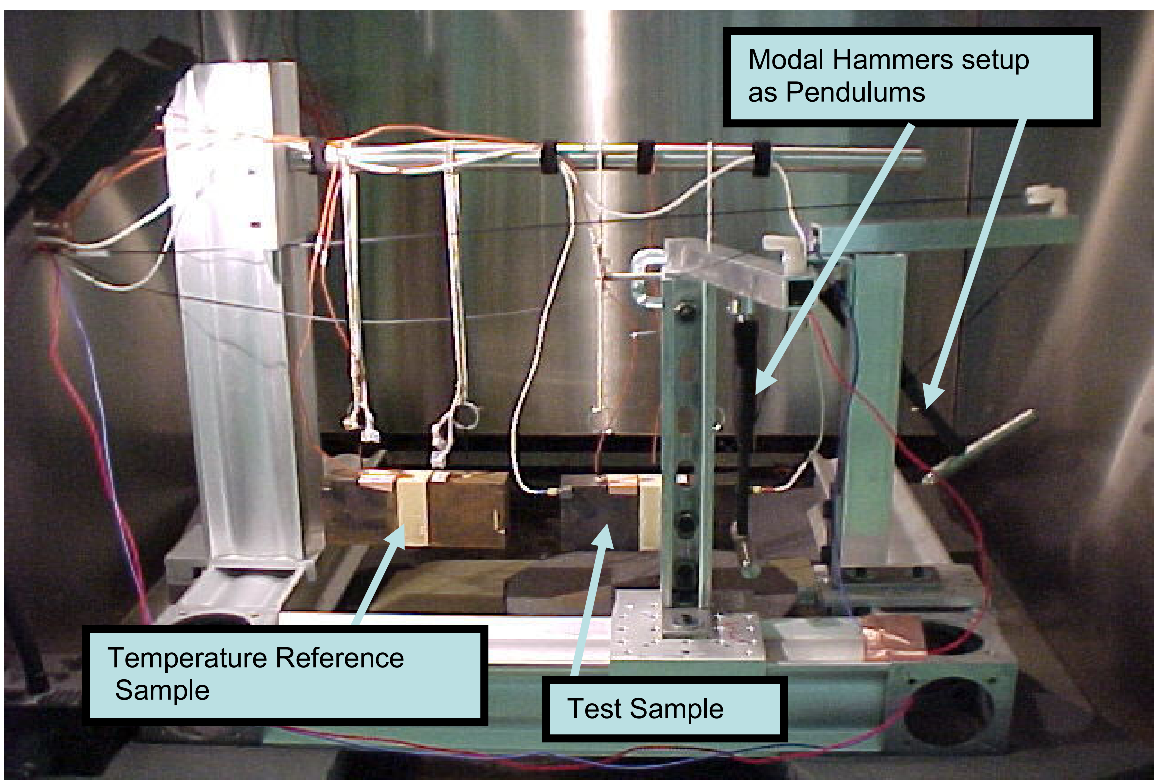

Figure 3. Sample setup in the climatic chamber.

A second sample was suspended next to the sample to be tested as a temperature reference to better quantify the uncertainty in the temperature. Four thermocouples were used. One thermocouple was imbedded in the center of the foam of the reference sample. The second thermocouple was placed on the top surface of the foam portion of the reference sample. A third thermocouple was placed on the top surface of the foam portion of the sample to be tested. A fourth thermocouple was suspended freely to measure the air temperature in the climatic chamber. The temperature in the center of the foam of the test sample was assumed to be close to the measured temperature in the center of the reference sample. It generally took approximately an hour for each sample to reach the given test temperatures in the climatic chamber.

Two modal hammers were arranged in a pendulum configuration in order to provide an input that would excite the sample's axial mode well and an input that would excite the torsion mode well. Figure 4 shows the positioning of the inputs.

During each modal test the sample was struck with a hammer equipped with a load cell which measured the input force. The accelerometers measured the resulting vibration. Frequency response data and time histories were recorded with averaging from several impacts.

Six dumbbell test articles were used in these tests that had foam densities given in Table 1.

Table 1. Foam densities in the dumbbell test articles.

Sample	Density lbs/ft3
A	17.94
B	17.7
C	18.92
D	17.95
E	20.33
F	20.28

Viscoelastic Model for EF-AR20

An earlier paper [1] described the development of a room temperature linear viscoelastic model for EF-AR20 epoxy foam. It was based on the combination of Dynamic Mechanical Analysis (DMA) test data and modal test data. The DMA tests were torsion tests performed at frequencies of 0.1 to 100 radians/sec frequency and at temperature increments of 10 degrees from -30 to 130 ^{o}C. The DMA test curves for each temperature were shifted into a single master curve of shear modulus versus frequency at room temperature. A Prony series model was then fit to the master curve. The torsional DMA tests could only provide shear modulus data. The modal test data provided a means for inferring the value of Young's modulus, Poisson's ratio, and damping at the discrete modal resonance frequencies and were also used to calibrate the final viscoelastic model.

For the current wide temperature application the master curve was established by shifting the individual DMA test curves to the glass transition temperature, Tg, for EF-AR20, which is 90 ^{o}C and recording the necessary shift (aT) in frequency/time for each temperature. The shift factor, aT, is the ratio of current time to reference or reduced time as given in Eq 1.

$$aT = \frac{t}{t_R} \qquad \text{Eq. 1}$$

The DMA test curve from the temperature of 60 ^{o}C had a shift factor of 1 x 10^7 to fit the master curve at 90 ^{o}C. Using only DMA temperature curves down to 60 ^{o}C in the master curve proved out to be more than enough to cover the frequency range of interest which is in the 500 to 2000 Hz range.

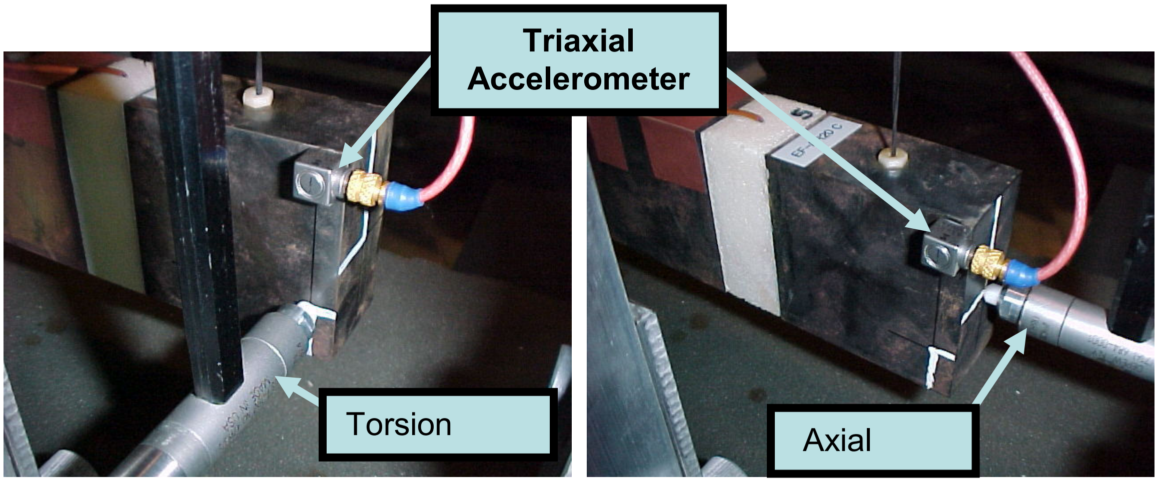

Figure 4. Positioning of the hammer impact locations.

Forming the master curve using 60 to 130 °C temperature range for the DMA curves resulted in a glassy and rubbery shear storage modulus values of Gg=10,860. psi and Gr =105. psi, respectively for a DMA sample that had a density of 18.5 lbs/ft^3.

Below 60 degrees C the glassy modulus was defined as a linear function of temperature as given in Eq. 2.

$$G(T) = 2.78 * Gg * (1 - 0.64 * T / Tg) \quad \text{for } T<Tg \qquad \text{Eq. 2}$$

These modulus values were scaled to other foam densities based on the modulus for this foam being proportional to density squared [1].
Figure 5 shows the master curve along with a 20 term Prony series fit to the master curve.

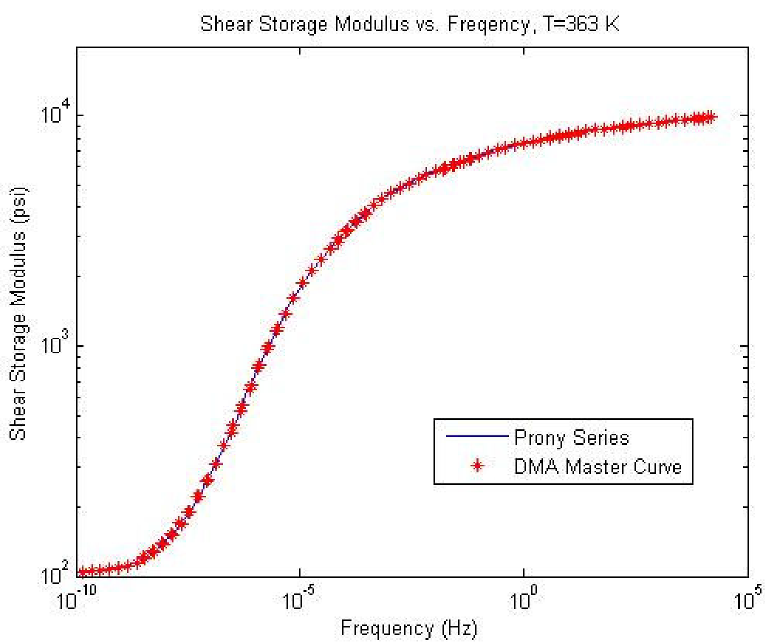

Figure 5. Master Curve for EF-AR20 at 90 °C based on DMA test data (Test S20r2) and Prony series model fit.

The form of the Prony series used is given in Eq. 3. This same series was also used for the foam's Bulk modulus.

$$G(t,T) = Gr + (Gg - Gr)\sum_{j=1}^{N} m_j \exp\left(-\frac{t}{aT(T)*\tau_j(T_{ref})}\right) \qquad \text{Eq. 3}$$

The Prony series coefficients, m_j, and time constants, τ_j, are given in Table 2.

Table 2. Prony series coefficients and time constants.

Index	Coefficients, m	Time Constants (sec)
1	7.47E-04	1.42E+08
2	2.48E-03	2.76E+07
3	5.04E-03	6.58E+06
4	1.50E-02	1.47E+06
5	3.30E-02	2.88E+05
6	3.90E-02	8.74E+04
7	5.93E-02	2.91E+04
8	7.90E-02	7.81E+03
9	9.35E-02	1.48E+03
10	1.07E-01	3.07E+02
11	8.93E-02	4.39E+01
12	7.97E-02	5.06E+00
13	8.13E-02	8.18E-01
14	6.48E-02	6.85E-02
15	6.35E-02	7.17E-03
16	4.35E-02	5.00E-04
17	3.55E-02	6.99E-05
18	3.54E-02	8.17E-06
19	3.65E-02	8.91E-07
20	3.64E-02	7.07E-08

The shift factor, aT, enables the time-temperature shifting of the master curve to other temperatures or frequencies. The Williams, Landel, Ferry (WLF) [5] equation, Eq. 4, was fit to the DMA shifting data for temperatures greater than Tg

$$\log(aT) = \frac{-c1*(T - Tg)}{c2 + T - Tg} \qquad \text{for } T > Tg \qquad \text{Eq. 4}$$

where c1=31.6, c2=111.5 degrees Celsius, T is the current temperature, Tg is the glass transition temperature. For temperatures below Tg the exponential equation, Eq. 5. was used

$$\log(aT) = 2.5(1 - \exp(0.09(T - Tg)) \qquad \text{for } T < Tg \qquad \text{Eq. 5}$$

Figure 6 shows a plot of Eqs 4 and 5 along with the DMA test shift data. Notice how the WLF curve fits the DMA shift data well above Tg but diverges from it below. The exponential curve also diverges from the DMA shift data

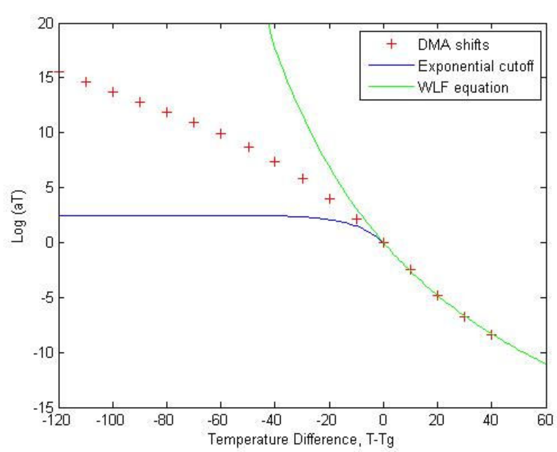

Figure 6. Time-temperature shifting function for EF-AR20 foam.

below Tg but was chosen to best match the apparent damping and shear modulus values measured in room temperature modal tests of dumbbell samples with EF-AR20 foam. The Prony series model has unrealistically low damping if the DMA shift data is followed closely below Tg. Combining Eqs 4 and 5 enable the damping to remain approximately constant along with the shift factor for temperatures below 60 degrees C.

Figure 7 shows a plot of the Prony series model predictions for shear storage modulus versus temperature compared with DMA test data at a 1 Hz excitation frequency. This comparison was used to calibrate the temperature dependence of the glassy shear modulus function in Eq. 2.

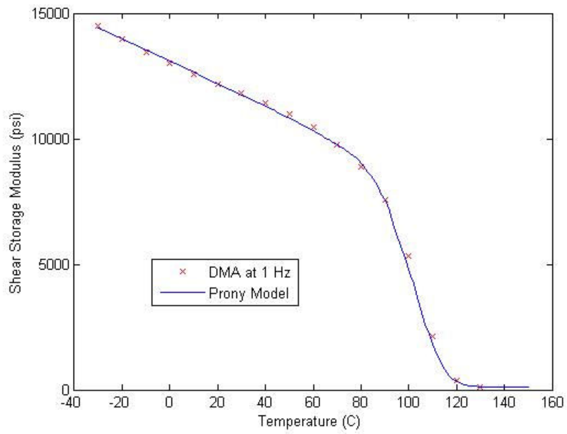

Figure 7. Prony series model with temperature dependent glassy modulus vs DMA test data for Shear Storage modulus versus temperature at 1Hz.

Figure 8 shows the model prediction of the Loss Tangent or Loss Factor compared with values from the DMA tests. This comparison was used to select the cutoff value of 2.5 for the time-temperature shift factor, aT, in Eq. 5.

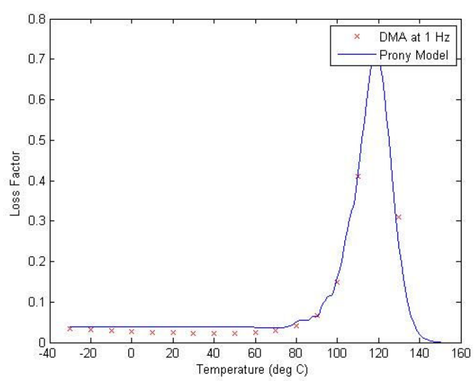

Figure 8. Model versus DMA and Tg test data for loss tangent versus temperature.

The final form of this viscoelastic model included an adjustment of the glassy storage modulus at room temperature [1] to allow the model to match with the modulus values coming out of the probabilistic model discussed later in the uncertainty quantification section.

Finite Element Model

The finite element model was composed of the Salinas structural dynamics code [3], the linear viscoelastic model already discussed, an elastic model for the steel blocks, and the finite element mesh as shown in Figure 9. This mesh was shown to converge to the first six modal frequencies within 1.3% [1]. The elastic properties for the steel were a Young's modulus of 30 x 10^6 psi and a Poisson's ratio of 0.3. The impact points and accelerometer output points are labeled.

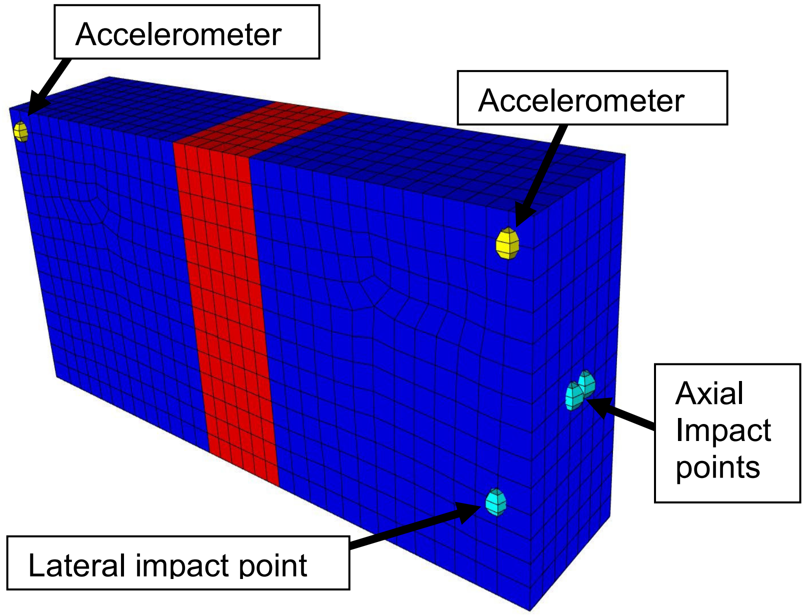

Figure 9. Finite element mesh for dumbbell test article; foam is the center block.

The finite element model was excited with a haversine shaped force time history as shown in Figure 10. The peak force, duration, and impulse were chosen to best fit the average hammer force time history from the tests. Matching the absolute excitation force characteristics of the test was important for using the validation metrics discussed later.

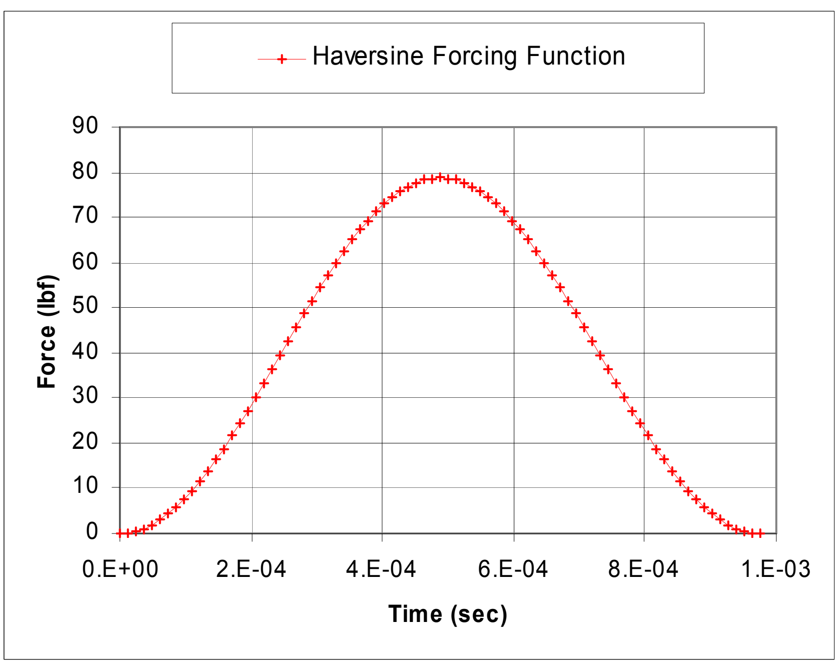

Figure 10. Haversine forcing function used in finite element model.

Uncertainty Quantification of EF-AR20 Foam Parameters

Experimental data at room temperature are available for the foam, and the approach to be used here is probabilistic. We first describe some previously established models [1], results, and list some assumptions.

The foam is EF-AR20. The foam model parameters are material density, ρ , modulus of elasticity, E, shear modulus, G, and viscous damping ratio, ζ . Extensive material tests indicate that all the material properties are somewhat random. The mean values of both modulus of elasticity and shear modulus are approximately square functions of the material density. Regression analyses can be used to accurately estimate the mean functions of modulus of elasticity and shear modulus, and random deviations from the mean functions can be assumed to have standard deviations that vary as square laws in ρ . Analyses of the EF-AR20 foam indicate that the deviations of the modulus of elasticity and the shear modulus from their respective mean functions are highly correlated with a correlation coefficient of about eighty-five percent, and high correlation between these two quantities will be assumed for all the foams. This high correlation indicates that the foam material Poisson's ratios will have small random variation, and this fact is observed from experiments. In view of these things, the modulus of elasticity, E, will be treated as a random variable, and the shear modulus will be computed from the formula

$$\mathrm{G} = \frac{\mathrm{E}}{2(1+\nu)} \qquad \text{Eq. 6}$$

where ν denotes Poisson's ratio, and its average value will be used to represent it. This implies that the relation between shear modulus and modulus of elasticity is approximated as deterministic, and that the correlation between these variables is perfect.

The material damping ratio measured at room temperature for EF-AR20 has a relatively small coefficient of variation, therefore, it will be represented with its mean value of 0.0145.

Given that the foam material parameters are random variables with fairly well-known models, there are numerous methods for establishing bounds associated with a particular probability of occurrence. We choose the following approach. Denote the material density random variable for the foam ρ . The random variable can be written in terms of a normalized variable via

$$\rho = \sigma_\rho Z_1 + \mu_\rho \qquad \text{Eq. 7}$$

where $(\mu_\rho, \sigma_\rho) =$ (18.32,1.75 lbs/ft^3), are the mean and standard deviation of the material density and Z_1, is a standard normal random variable.

Denote the modulus of elasticity for the foam *E*. The modulus of elasticity can be written in terms of a normalized variable via

$$E = \alpha\rho^2 + \sigma_0\rho^2 Z_2 \qquad \text{Eq. 8}$$

where $\alpha = 0.118$ is the regression coefficient for the foam, $\sigma_0 = 0.00635$, is the standard deviation of the modulus of elasticity for the foam (both yield E in units of ksi when the density is in lbs/ft^3), and Z_2 is a standard normal random variable, uncorrelated with Z_1.

We assume that the deviation of the modulus of elasticity from its mean is independent of the foam material density. Therefore, the random variables Z_1 and Z_2 are independent. In view of this, we can define a chi squared-distributed random variable with two degrees of freedom

$$\chi_2^2 = Z_1^2 + Z_2^2 \qquad \text{Eq. 9}$$

The probability that any realization of the chi squared random variable lies outside the circle with radius *r* is

$$P\left(\chi_2^2 > r^2\right) = 1 - F_{\chi_2^2}\left(r^2\right) \qquad r^2 \geq 0 \qquad \text{Eq. 10}$$

where $F_{\chi_2^2}(\bullet)$ is the cumulative distribution function of a chi squared distribution with two degrees of freedom.

To establish bounds with a specific probability of being surpassed on the random parameters of the foams, we simply infer a value of *r* from the probability statement of Eq. 10, then use it in Eq. 9 to establish a limiting expression for the bounds on the normalized transforms of the parameters Z_1 and Z_2. Because the bounding variables denote specific sets of parameters, we replace the Z_1 and Z_2, with z_1 and z_2. Thus, the formula

$$r^2 = z_1^2 + z_2^2 \qquad \text{Eq. 11}$$

governs combinations of the normalized variates z_1 and z_2 that can be used to establish bounds on the foam density and its modulus of elasticity. Eq. 11 is clearly satisfied by an infinite set of combinations of z_1 and z_2, that lie on the perimeter of the circle with radius *r*, so the question is: what combinations of the variables do we choose to establish limits on the foam parameters? Given Eqs. 7 and 8 and the constraint of Eq. 11 we cannot simultaneously maximize the weight density and the modulus of elasticity, though we can simultaneously minimize them. Therefore, we choose to select the density and the modulus of elasticity by maximizing the quantity S defined in Eq. 12

$$S = \sqrt{\left(\frac{\rho}{\rho_{\max}}\right)^2 + \left(\frac{E}{E_{\max}}\right)^2} \qquad \text{Eq. 12}$$

where ρ_{max} is the absolute maximum value of density computed using Eq. 7 with z_1 values from Eq. 11, and E_{max} is the absolute maximum value of modulus of elasticity computed using Eq. 8 with z_1 and z_2 from Eq. 11.

When we choose to establish limits corresponding to a ninety-five percent probability region, i.e., limits associated with a five percent probability of being surpassed, the radius of Eq. 11 is $r = 2.4478$. This is the ninety-five percentile probability point of a chi squared distribution with two degrees of freedom and can be obtained from any table of percentage points of the chi squared distribution. The permissible values of z_1 and z_2 are shown as the perimeter of the circle in Figure 11. Clearly, the z_1 and z_2 pairs are constrained to the circle, are related to one another, and can be expressed

$$z_1 = r\cos\theta \qquad z_2 = r\sin\theta \qquad \text{Eq. 13}$$

where θ is the angle in radians referenced in Figure 11.

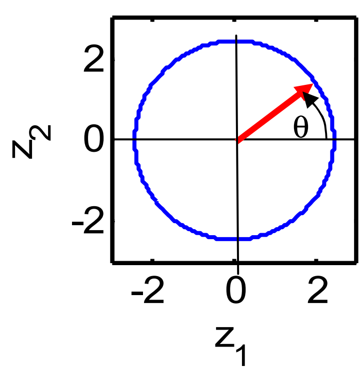

Figure 11. Values of z_1 and z_2 that satisfy Eq. (7) with $r = 2.4478$.

When the combinations of values of z_1 and z_2 shown in Figure 11 are used in Eqs. 7 and 8 the possible values of weight density and modulus of elasticity are established, and these are plotted in Figure 12 as a function of θ.

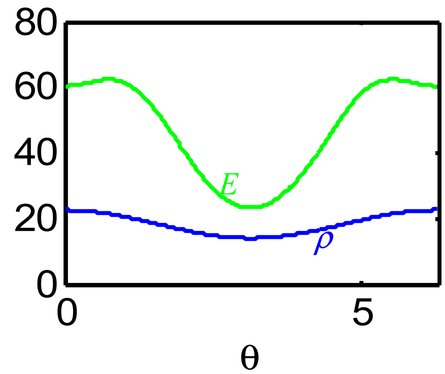

Figure 12. Values of weight density and modulus of elasticity corresponding to the values of z_1 and z_2 shown in Figure 11.

The values vary as the combinations of z_1 and z_2 proceed around the circle, i.e., as θ varies over the interval $[0,2\pi]$ radians.

The normalized values of weight density and modulus of elasticity were computed and are shown, along with the function of Eq. 12, in Figure 13, plotted as a function of θ.

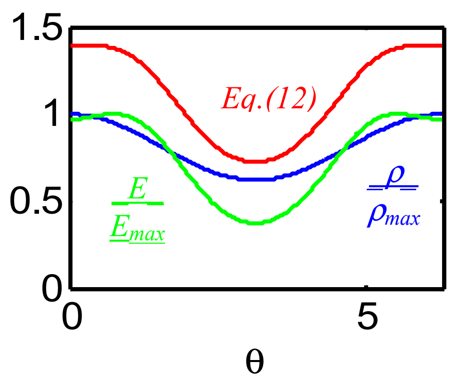

Figure 13. Normalized weight density, modulus of elasticity and the function of Eq. 11.

The quantity "S" in Eq. 12 is minimized for the weight density and modulus of elasticity if

$$\rho = 14.0\, lb/ft^3 \qquad E = 23.2\, ksi \qquad \text{Eq. 14}$$

and these values correspond to the z_1 and z_2 values $z_1 = -2.4478, z_2 = 0$. The quantity "S" in Eq. 12 is maximized for the weight density and modulus of elasticity if

$$\rho = 22.4\, lb/ft^3 \qquad E = 61.6\, ksi \qquad \text{Eq. 15}$$

and these values correspond to the z_1 and z_2 values $z_1 = 2.3232, z_2 = 0.7710$.These are joint realizations of weight density and modulus of elasticity that may be used to represent ninety-five percent probable limits, i.e., joint limits with a five percent probability of being surpassed.

The mean measured value of Poisson's ratio for EF-AR20 foam is $\nu = 0.28$, therefore, the minimum and maximum values of the shear modulus corresponding to the moduli of elasticity in Eqs. 14 and 15 are

$$G_{min} = 9.06\text{ ksi} \qquad G_{max} = 24.1\text{ ksi} \qquad \text{Eq. 16}$$

The lower/upper bound parameter values representing the ninety-five percent probable limits for the EF-AR20 foam are summarized in Table 3.

Table 3. Ninety-five percent probable limits for EF-AR20 foam parameters.

	ρ lbs/ft^3	***E*** *ksi*	***G*** *ksi*	ζ damping
Lower bound	14.0	23.2	9.06	0.0145
Upper bound	22.4	61.6	24.1	0.0145

Validation

The lower/upper bound values for the density and modulus values will now be used for the model validation process. Two types of Salinas runs were performed using the model shown in Figure 9 for comparing model predicted results with test data. The first type of runs were eigenvalue solutions and the second type were transient solutions which used the upper/lower bound values to calibrate the viscoelastic model to existing room temperature data. This validation process was done in a double blind fashion. Neither the test engineer nor the analyst saw each other's data before the model predictions were made.

The eigenvalue solutions involved using a linear elastic model for the foam in the dumbbell and iterating on the shear modulus and Young's modulus to match the torsion and axial modes (both frequency and model shape) from the tests. These runs were effectively post processing runs on the test data and provided estimates for the effective linear elastic moduli of the foam versus temperature and were treated as test results. This enabled the use of the modulus versus temperature metric to be applied for model validation. Figure 14 shows the comparison of shear modulus values inferred from the modal tests with values coming directly out of the viscoelastic model. Three curves represent the model predictions in terms of the upper-bound, lower-bound, and nominal values. The lower/upper bound values are based on adjusting the viscoelastic model using Table 3 results, whereas the nominal results are based on Eq. 8 for the modulus values to adjust the glassy modulus as discussed earlier [1]. The upper- and lower-bound curves very nicely envelope the test data as desired. Moreover, the nominal model or deterministic prediction agrees very well with the Test B results.

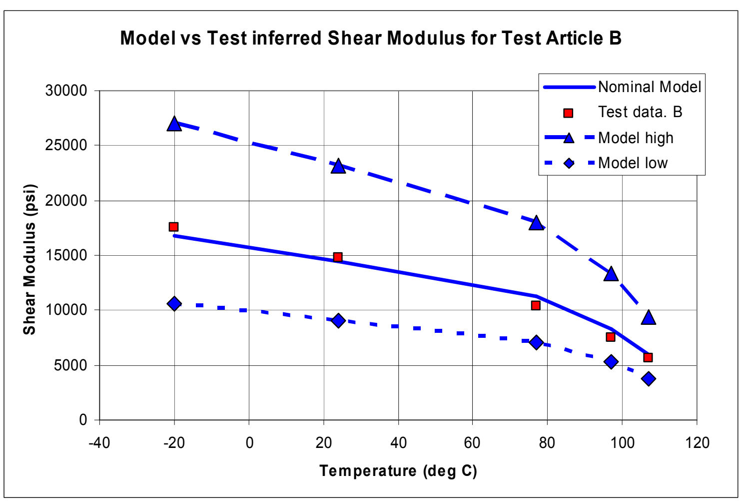

Figure 14. Model predictions compared to test data for shear modulus versus temperature.

Figure 15 shows a comparison of the damping for axial and torsional modes measured in the modal tests compared with values from the viscoelastic model at the same temperatures and frequencies. Here the damping is calculated as one half of the loss tangent coming out of the viscoelastic model since the foam is the primary flexible material in the dumbbell configuration. The model agrees very well with test values at elevated temperatures down to room temperature. However, the damping in the model does not increase going below room temperature as the test data implies. Consequently, the model is expected to over predict motion at -20 degrees C which would make it a conservative model.

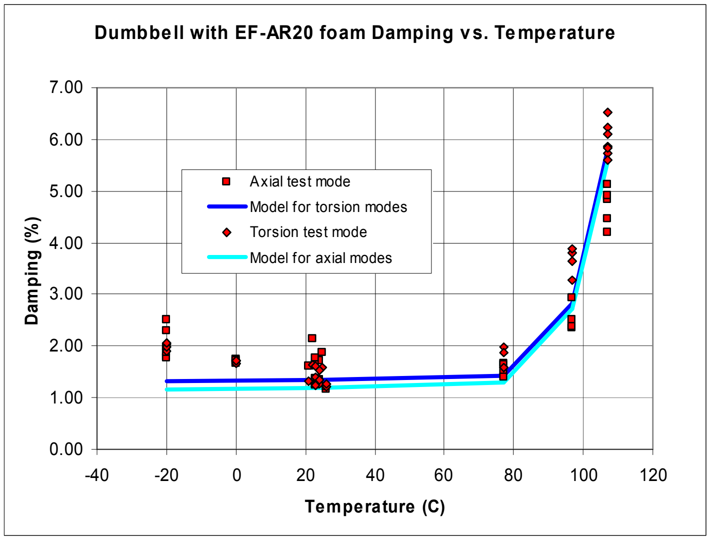

Figure 15. Model predicted damping compared to modal test measurements.

The second set of Salinas runs were simulations of the actual modal tests on the dumbbell test articles. They were transient solutions using the haversine function shown in Figure 10 to excite the dumbbell model in the axial and lateral directions . The model validation metrics that are most closely connected to the application of the foam are peak acceleration and shock response spectra in the time domain and a windowed frequency response function approach in the frequency domain. These metrics will be applied to the transient test data. In order to compensate for variation in the input forcing function, the peak acceleration and shock response spectra will be divided by the input impulse value which is similar to the way a frequency response function or transfer function is calculated. Validation of the model using the transient results is currently in progress.

Conclusions

A linear viscoelastic model was calibrated for EF-AR20 foam over a temperature range of -20 to 110 degrees C and implemented in the Salinas finite element code. The calibration process used Dynamic Mechanical Analysis constitutive test data over the full temperature band and modal test data from room temperature tests. Also, validation modal tests have been conducted over the full temperature band. Foam density and Young's modulus were treated as random variables in the viscoelastic model. Predictions were made for the validation experiments in preparation for model validation. Two validation metrics were applied and three more validation metrics were mentioned that are planned to be used. Results from the shear modulus versus temperature metric look very good for the model's validity. The damping metric shows the model to be valid over the full temperature band with a caveat that the model is expected to over predict accelerations for temperatures below room temperature.

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