STUDY OF PSA AS VIBRATION DAMPING LAYER

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Abstract

The paper presents an application based approach to optimizing PSAs for use in vibration damping applications.

The paper addresses the use of predicting damping performance of composites based on the rheological properties of PSA. The presented modeling approach outlines a method of relating rheology properties to reducing vibration in a beam application with corollaries to use in automotive body structures and vehicle applications. In order to gain a better understanding of the physical phenomena, the material properties are modeled via a simplified Finite Element and the useful output is discussed.

Given the model for predicting performance, a series of trade studies are presented to show the impact of modulus properties on the resulting composite damping performance. Consideration is given to the material property changes as observed with temperature and frequency change.

Finally practical design considerations are explored for using PSAs in application. The impacts on vibration reduction potential are compared to typical failure modes of PSAs. An effort is made to correlate common failures with material properties of damping materials. Consideration will be made to understand potential downstream failures and determine appropriate design constraints.

1.0 Introduction

Pressure sensitive adhesives have commonly been made from visco-elastic materials to enhance essential functional characteristics such as initial tack, peel adhesion and shear resistance. The fluid like properties of the visco-elastic PSA have been shown to enhance the initial wet out of surfaces while the modulus has been shown to give resistance to debonding [1]. Unlike other adhesives, PSAs are unique in that they do not undergo a change in physical state between bonding and functioning as an adhesive [2]. The resulting constant physical state ensures that the liquid and solid states are always presence in the adhesive. In order to identify the ideal fluid and solid balance of a PSA, the rheology has been studied at length to enhance its adhesion and application properties.

The rheological properties of visco-elastic materials, in this case PSAs, have been shown to depend on temperature, frequency, strain rate, and in certain cases pre-stresses [3]. While the Temperature and strain rate dependence have been primary means of exploiting rheology properties for adhesion, the presented study will review the generalized temperature and frequency interdependence. Further, the resulting combination of visco-elastic properties in a vibrating composite and the resulting dissipate mechanical vibration detailed.

The use of polymeric visco-elastic materials in vibration damping has been researched extensively. Damping through the application of thick polymeric patches to vibrating substrates was first described by Oberst in 1952. The application of visco-elastics sandwiched between a vibrating substrate and a sacrificial constraining layer was further developed by Ross, Ungar, and Kerwin in 1959. Together, extensional damping and constrained layer damping respectively are two common methods of increasing the composite damping of a substrate and visco-elastic material composite [4]. Further, the advent of Finite Element modeling has enabled closer looks at strain relationships for visco-elastic materials in vibrating situations.

Given the advent of PSAs technology and the inherently damping rheology, PSAs have taken the place of several thicker Polymeric materials as damping layers. While this method for creating a constrained layer damping composite has obvious advantages of combining the visco-elastic material and the attachment methodology associated with traditional constrained systems, it introduces the several non-optimal conditions requiring trade off.

Creating damping composites with PSAs requires simultaneously satisfying the basic properties for adhesion and the properties required to dissipate application specific structural vibrations over broad frequency and temperature ranges. Additionally, durability concerns need to be addressed. The outcome of this study is an in-depth looks at property required to create a windowed region of performance.

2.0 Damping Theory & Model

As previously stated, extensional damping and constrained layer damping are two developed methods for increasing the damping within a structure. Typical extensional and constrained layer damping cross sections are shown in Figure 1 and Figure 2 respectively.

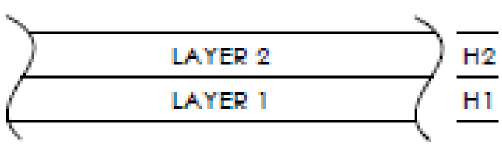

Figure 1: Extensional Damping Cross Section

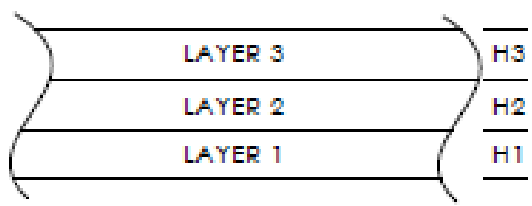

Figure 2: Constrained Damping Cross Section

Many methods have been employed to describe the response of a damped system with the Ross-Kerwin-Ungar, RKU, being the most widely accepted in describing damping characteristics. The constituent equations for a three layer constrained system are described for a thin beam in Equation 1 [5]. The constituent equation for an extensional damping system can be obtained by allowing $H_3 \rightarrow 0$, $E_3 \rightarrow 0$, and the shear parameter $g \rightarrow \infty$ as outlined also in reference [5].

Equation 1

$$EI_c(1+i\eta_c) = E_1\frac{H_1^3}{12} + \mathrm{E}_2^*\frac{H_2^3}{12} + E_3\frac{H_3^3}{12} - \mathrm{E}_2^*\frac{H_2^2}{12}\left(\frac{H_{31}-D}{1+g}\right) + E_1H_1D^2 + \mathrm{E}_2^*H_2(H_{21}-D)^2 + E_3H_3(H_{31}-D)^2 - \left[\frac{\mathrm{E}_2^*H_2}{2}(H_{21}-D) + E_3H_3(H_{31}-D)\right]\left(\frac{H_{31}-D}{1+g}\right)$$

$$E_2^* = E_2(1 + i\eta_2)$$

$$g = \frac{G_2(1 + i\eta_2)}{E_3 H_3 H_2 p^2}$$

$$D = \frac{E_2^* H_2 \frac{H_{21} - H_{31}}{2} + g(E_2^* H_2 H_{21} + E_3 H_3 H_{31})}{E_1 H_1 + \frac{E_2^* H_2}{2} + g(E_1 H_1 + E_2^* H_2 + E_3 H_3)}$$

$$H_{31} = \frac{H_1 + H_3}{2} + H_2$$

$$H_{21} = \frac{H_1 + H_2}{2}$$

Where

E_i = Real Elastic Modulus of layer i

G_i = Real Shear Modulus of layer i

H_i = Thickness of layer i

I_i = 2nd moment of Inertia of layer i

p = Wave Number

η_i = loss factor or tan δ of layer i

As the RKU equation has significant number of variables, it is easiest to understand the influence of Layer 2 material rheology through application. For explanation purposes, a 1.5 mm (60 mil) Aluminum substrate will be assumed with a wavenumber of 53.41 corresponding to the 17th modal frequency. The 17th mode is approximately 1 kHz for the simply supported 1m long aluminum beam. Note, the modal frequency will change with the addition of damping treatments. A comparison between extensional and constrained layer damping is presented in Figure 3.

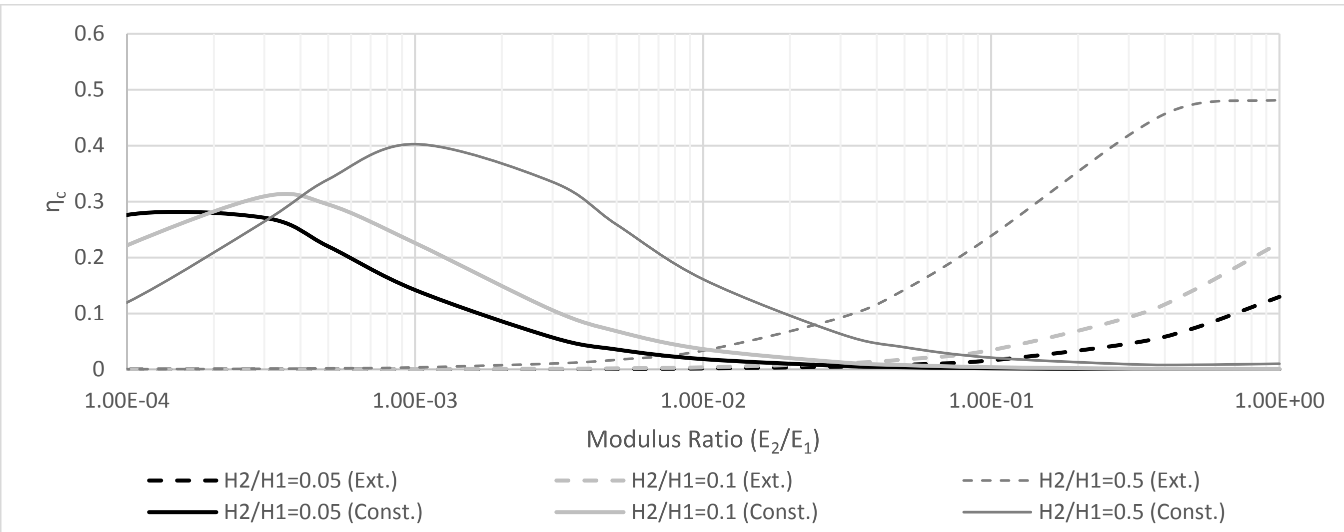

Figure 3: Comparison of Extensional and Constrained damping performance. In the example η_2=1. E3/E1=H3/H1=1 for the constrained damping.

From Observation, the extensional damping has several simplifying characteristics. The composite Damping, η_c, is directly proportional to the damping of Layer 2, η_2. Increasing the thicknesses of layer 2 results in increases of composite damping. Further, higher composite damping is achieved with higher ratios of real elastic modulus of Layer 2 to Layer 1. Appreciable composite damping is observed for $\frac{E_2}{E_1}$>1e-2 for most practical application thicknesses.

In practicality, increasing modulus is typically accomplished by the addition of fillers agents which have high molecular weight. Similarly, increasing the thickness of the Layer 2 is accomplished by adding mass to the system. While extensional damping is effective, all practical increases in the composite damping outside of raising η_2 result in significant weight increases.

While more complex, constrained damping can increase the composite damping with less material thickness at lower modulus. The net result is the potential of decreased composite mass. The potential for decreased mass and increased performance relies on a balance of material properties and constraining layer thicknesses to result in the maximized stiffness increase due to Layer 2. As constrained layer has significant complexity, the presented application will again be based on 1.5 mm (60 mil) Aluminum substrate at the 17^{th} modal frequency.

In order to understand the effect of Layer 2 modulus, E_2, with increasing Layer 3 thickness, H_3, analysis was performed and presented in Figure 4. The figure illustrates an optimal combination exists for each modulus value and each constraining layer thickness. The non-obvious trend shows for low modulus ratios of the Layer 2 to Layer 1, the peak damping amplitude decreases. As the modulus ratio increases, the peak damping amplitude also increases until a maximum damping amplitude is reached. As modulus ratio is further increased, composite damping performance decreases. Interestingly, as modulus is further increased past the point of optimal constrained damping, a peak in damping is observed as $H_3 \rightarrow 0$ which is attributed to extensional damping characteristics.

Given the shifts in composite damping with changing modulus, the influence on composite damping for varying thickness of Layer 2 and Layer 3 was found in Figure 5. Contrary to the extensional damping, the combination studied was found to have composite damping peak amplitude increases for decreased ratios of H_2 to H_1. This trend can be shifted as shown in Figure 3, but has been found to be applicable to multiple PSA modulus ranges of interest. The obvious conclusion of this interaction is a potential weight reduction potential using a PSA as damping composite over a stiff and thick extensional damping material.

Peak damping amplitudes are found to increase as the ratio of Layer 3 to Layer 1 thicknesses approach unity. Specialized applications have shown composite damping to slightly increase after unity for specific modulus combinations, but diminishing return in performance versus the added cost and weight of a heavy constraining layer coupled with the decrease in bond strength for low modulus typically make this impractical for PSAs and outside of the topic. In application, having thickness ratios of unity are often times impractical for PSAs given the added cost, weight, and installation concerns associated with thick constraining layer. In practice, most ratios of Layer 3 to Layer 2 thicknesses are in the 0.1 to 0.5 range due to these additional concerns.

Interestingly there is a shift in peak composite damping amplitude versus ratios of constraining layer and substrate thicknesses as shown in Figure 4 & Figure 5. As previously stated, this is a non-obvious characteristic given the constant material modulus, E_2, and loss factor, η_2, for each example. To explain the shift in peak damping the interaction between the three layers and the resulting resonant frequency of the system was studied. Again focusing on the 17^{th} modal frequency, a comparison is shown for the resulting modal frequencies and composite loss factor for the entire damped system for a simply supported beam in Figure 6. The figure is plotted versus increased ratio of Layer 2 storage modulus, E_2, to substrate modulus, E_1.

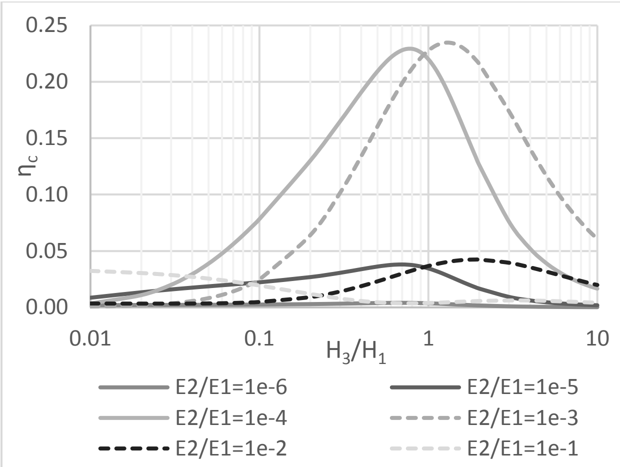

Figure 4: Constrained Damping for $E3/E1=1$, $H2/H1=0.1$, $\eta_2=1$

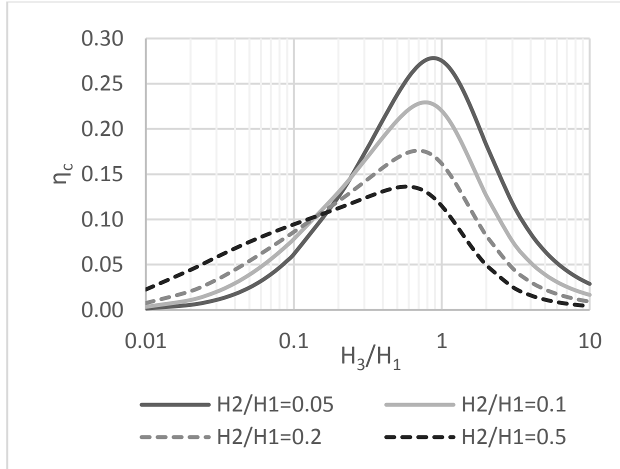

Figure 5: Constrained Damping for $E3/E1=1$, $E2/E1=1e\text{-}4$, $\eta_2=1$

The results presented in the figure have physical interpretation. At low modulus ratios corresponding to low frequencies or high temperatures, the modal frequency is dominated by the substrate. In this scenario, Layer 3 is pseudo isolated from the motion of the substrate. At high modulus ratios corresponding to high frequencies or cold temperatures, smaller amounts of shearing occur in Layer 2, and the three layers move together. For modulus ratios between these two extremes, the influence of the Layer 2 modulus is the greatest and hence a peak in composite loss factor is observed.

Of note is the similarity of the response of the three layer composite shown in Figure 6 to the rheology of a homogeneous PSA material. Given that frequency is directly proportional to the square root of storage modulus, a typical PSA material will have a rubber plateau, transition, and glass plateau with a peak damping in the transition as shown. While the figure represents a design study, the same general principals are happening on a macro scale as with the PSA polymer. In the pseudo glass region, the constituents are locked together while in the rubber region the layers move more independently of one another. In the transition, there is an interaction associated with the relative motion and geometric shift of the layers as similar to the molecular level of a polymer. Further, the larger difference between the glass and rubber plateaus as the result in this design study from increasing constraining layer thickness, raises the potential composite loss factor amplitude. As such, the difference in Layer 1 & 3 thickness dictate the pseudo transition range modulus span and results in both shifted peak composite damping amplitude and the ratio of modulus at which it occurs.

Comparing extensional versus constrained layer damping, specific characteristics can be determined. Specifically, thick layers of high modulus materials are required for extension damping. While constrained layer damping has the added complexity. Ideal constrained damping materials are thin and have low modulus as found with PSAs. In terms of rheology, constrained layer damping materials typically use PSA materials in the temperature range above peak η_2, i.e. $T_{useful} > T_{peak\ \eta 2}$, or frequencies lower than peak η_2, i.e. $f_{useful} < f_{peak\ \eta 2}$. As temperature and frequency are related through time-temperature superposition, reduced frequency nomograms can be created. The ideal regions for extensional versus constrained layer damping are outlined in Figure 7.

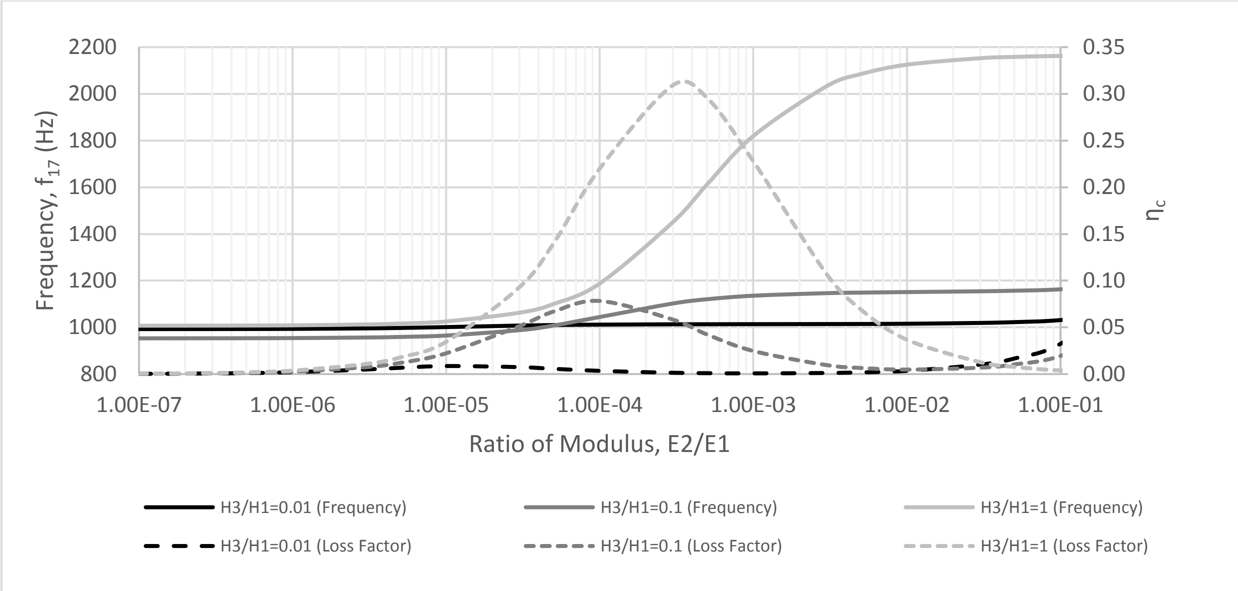

Figure 6: Constrained Damping for E3/E1=1, η2=1, H2/H1=0.1, ρ3/ρ1=1, ρ2/ρ1=0.4

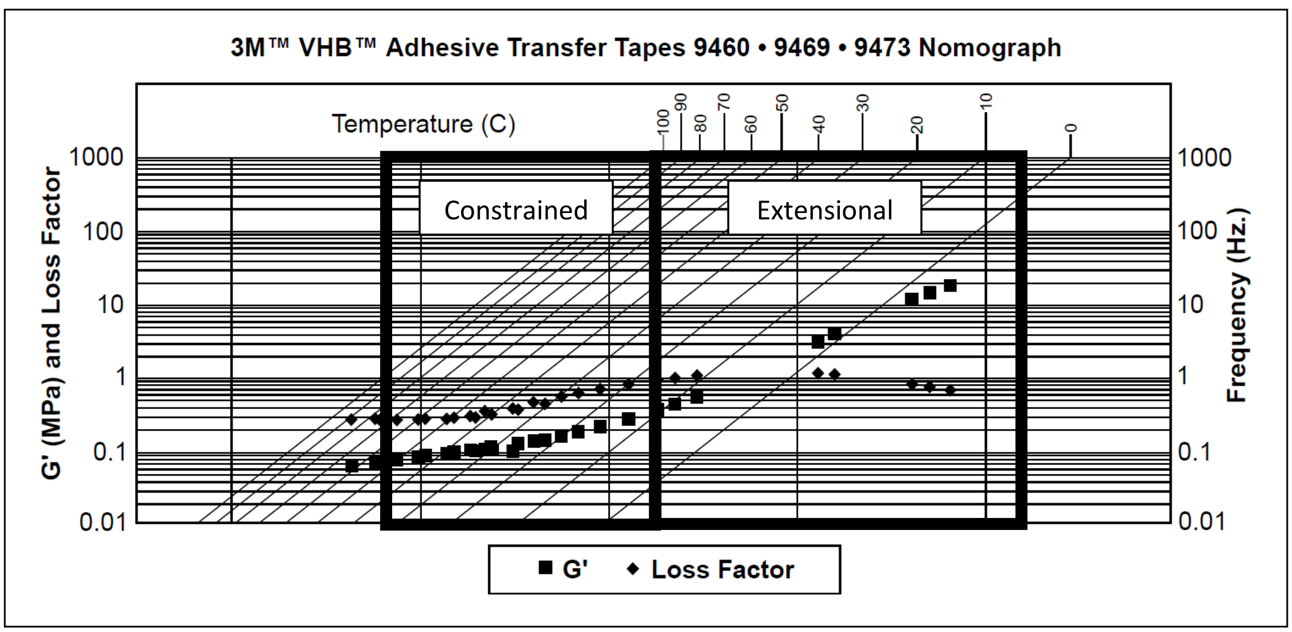

Figure 7: Regions of use of use on frequency nomogram for 3M VHB PSA [6]

3.0 Finite Element Model

To this point, the subject of the paper has hinged on illustrating the optimal composite damping response based on the RKU equations. While practical for preliminary ideation, to implementation of the RKU as a means of developing ideal rheological properties can be limiting based on its strict adhesion to idealized beams, boundary conditions, uniformity in treatment, and sinusoidal excitation assumptions.

Of more interest is a method for optimizing damping response which will also show mega trends of the composite in application.

In order to overcome the limitations of the RKU equations and to provide greater insight into the effect of modulus on composite properties, finite element (FE) was used. A grossly simplified FE model consisting of elastic elements in 2D was used to evaluate relative motion. Both model constraints are for simplified study and can be easily extended in practice to encompass real structures with applicable PSA material models as required.

The same one meter aluminum bar was modeled as a solid using 8-node biquadratic plane stress quadrilateral elements in Abaqus simulation software by Dassault Systèmes Simulia Corp. Aluminum was again assumed for the substrate, and the study relations as presented in Figure 6 *were incorporated with the exception of damping. Initial checks of beam natural frequencies were found via modal analysis and similar influence in the frequency of the 17th mode are shown in*

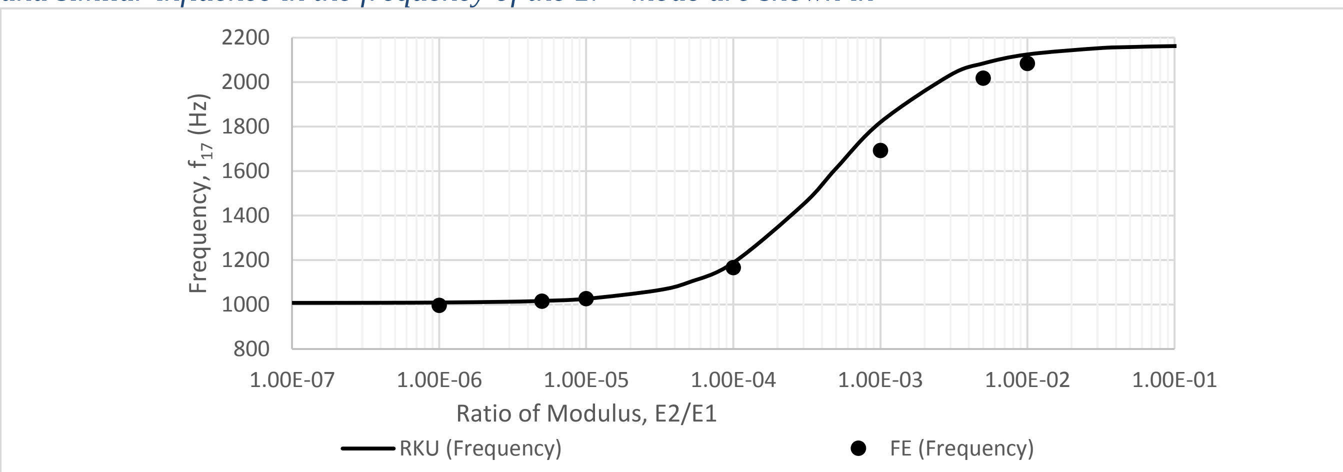

Figure 8 confirming similar elastic performance as expected. Slight differences in natural frequency between RKU and FE are attributed to the inclusion of only elastic elements in the FE model without complex modulus for simplicity of modal analysis.

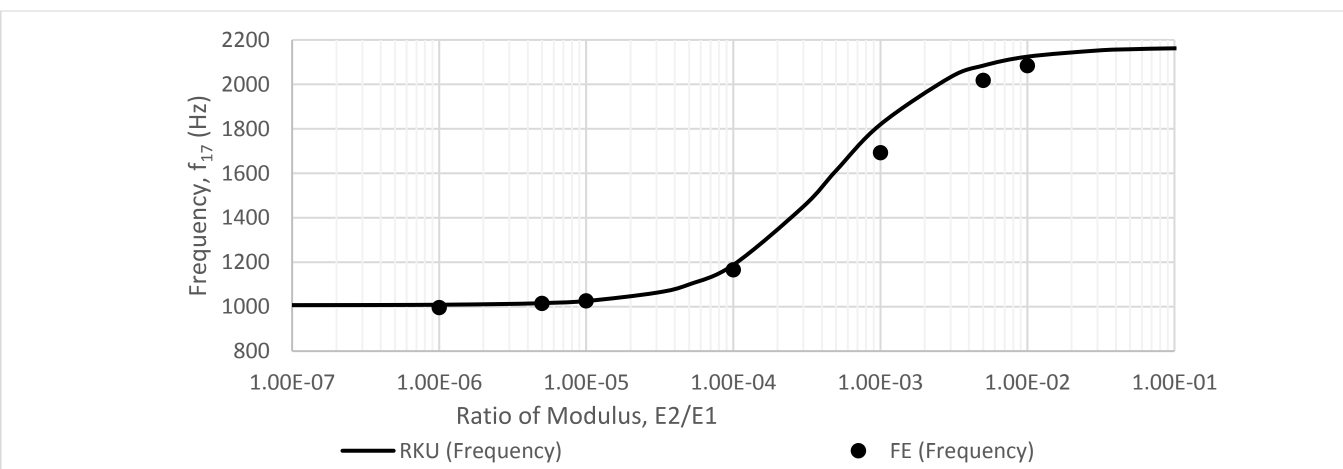

Figure 8: Constrained Damping for E3/E1=1, η2=1, H2/H1=0.1, ρ3/ρ1=1, ρ2/ρ1=0.4

Reviewing the change in average strain versus modulus change shows more insight into the mechanics of the damping composite as shown in for composite loss factor prediction

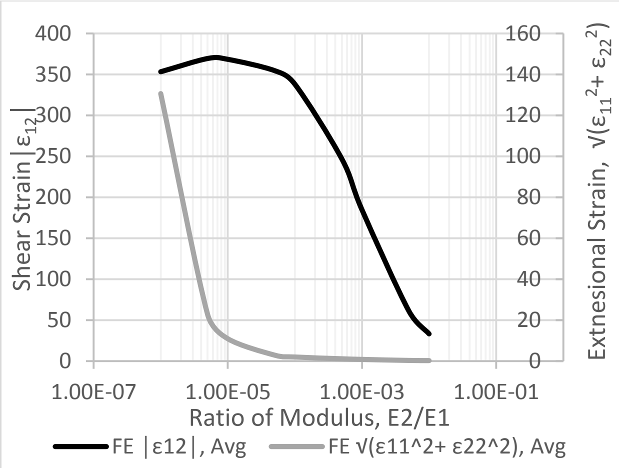

Figure 9. Extensional strain of Layer 2, ε_{11}, in the direction of the bar is relatively small given that the layer is coupled by Layer 1 & 3 dimension. Average compressional strain of Layer 2, ε_{22}, through the thickness conversely is relatively large as is average shear strain, ε_{12}. More importantly, the rate at which the two strain parameters change vary dramatically with modulus. While both terms increase with decreased modulus, the compressional term increases at a much higher rate at lower values driven by compression at anti-nodes and end effects. In essence, the bending stiffness of the Layer 2 is insignificant or at least compliant relative to Layer 1 & 3 in these areas at low modulus. The overall impact of Layer 2 will not influence the bending stiffness of the total composite. The bending stiffness impact correlates to the first three terms of the RKU equations which detail the bending stiffness of the composite, i.e. $E_i \frac{H_i^3}{12}$ and the resulting decrease in bending moment due to reduced rotation of Layer 3 from Layer 2 via the $-\mathrm{E}_2^* \frac{H_2^2}{12}\left(\frac{H_{31}-D}{1+g}\right)$ term.

The shear strain typically increases at reduced modulus values, however, the rate of increase is less than the compression for low values of modulus. The shearing force applied to Layer 2 is from the extension of Layer 3. The shearing force from Layer 3 will plateau after a critical modulus where all rotation motion from the flexure of Layer 1 is relaxed in Layer 2, i.e. the rotation does not force Layer 3 to extend. As the shearing force plateaus and strain is directly proportional to force normalized by modulus, the strain plateaus and even decreases shown in for composite loss factor prediction

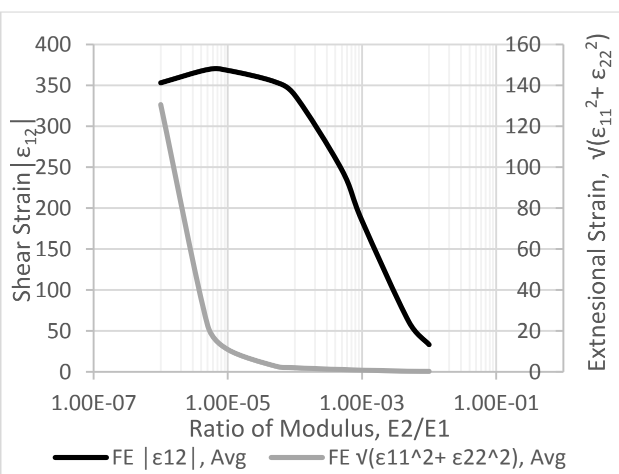

Figure 9. This change in more fully described by the RKU equations taking actual change in angle into account via the last terms of the equation, i.e. $E_2^* H_2 (H_{21} - D)^2 + E_3 H_3 (H_{31} - D)^2$ & $-\left[\frac{E_2^* H_2}{2}(H_{21} - D) + E_3 H_3 (H_{31} - D)\right]\left(\frac{H_{31}-D}{1+g}\right)$ with the first set of terms describing the bending moment induced by forces a given distance from the neutral axis and the second term detailing the reduction in bending moment due to the reduction in force from reduced rotational from the interaction of Layer 2 & 3.

The strain and shear of Layer 2 was shown dependent on the Layer 1& 3 and the modulus. Further, the physical explanation of the RKU equations related the total composite damping to the material properties of Layer 2. An obvious correlation for damping is between the strain energy of Layer 2 to the total strain energy of the entire system. The relationship between composite loss factor and strain energy has been shown as $\eta_c = \eta_2 \frac{SE_{Layer2}}{SE_{Total}}$ [7]. The total strain was calculated by summing the element strain energy as found in FE. As can be seen, the peak in ratio of total strain energy correlate to optimal damping in the composite as shown in Figure 10. Given that the FE model was calculated without damping, and the RKU equations were found per Section 3 with a Layer 2 loss factor of unity, the RKU loss factor and ratio of strain energies are directly related to one another. While the ratio of strain energies is not a direct measure of damping, it can be used during design of non-simplified geometries for composite loss factor prediction

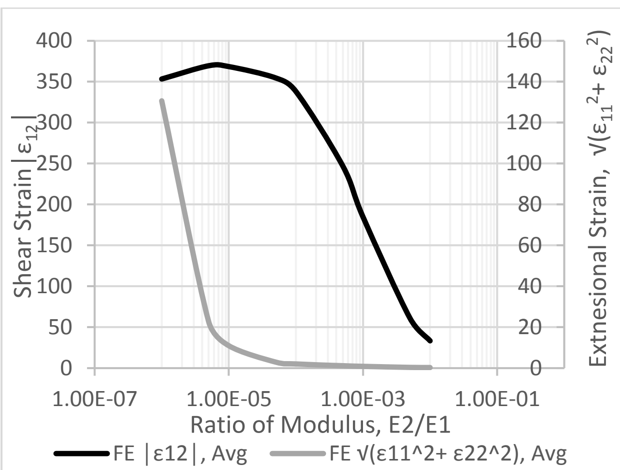

Figure 9 Constrained Damping for E3/E1=1, η2=1, H3/H1=1, H2/H1=0.1, ρ3/ρ1=1, ρ2/ρ1=0.4

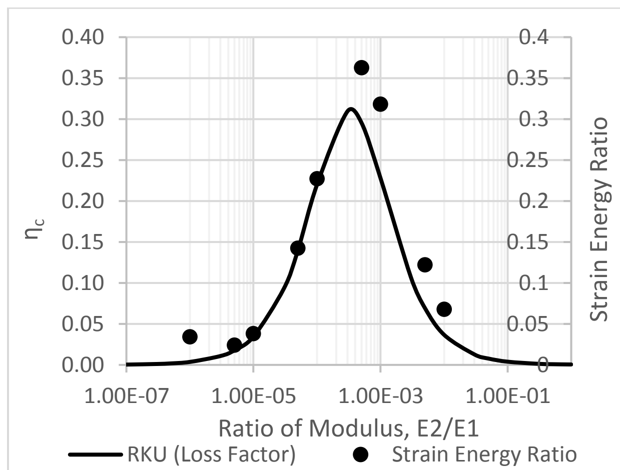

Figure 10: Constrained Damping for E3/E1=1, η2=1, H3/H1=1, H2/H1=0.1, ρ3/ρ1=1, ρ2/ρ1=0.4 compared to FE Strain Energy Ratio

4.0 PSA Design Considerations

Given that the damping PSAs have been correlated to rheological properties and the motion of the PSA layer, a review of practical design limitations is presented. Specifically, the criteria for creating a constrained layer damping system with PSAs will be compared to functional characteristics such as tack, peel adhesion, shear resistance and thermal resistance.

In order to damp efficiently, it is shown that the modulus ratio for the PSA to the substrate, E_2/E_1, should be between 5E-5 & 5E-3. Given the example of Aluminum as the substrate, the range for storage modulus for the viscoelastic layer is approximately 3.5 MPa to 350 MPa. This value is contrasted against the Dahlquist criterion for tack at 1 second. The Dahlquist criterion requires the $|E_2(1 + i\eta_2)| \leq 1MPa$ [2]. This criteria is not met within the modulus range of application damping potentially leading to poor tack. While the application frequencies are typically not at the same frequency as the low frequency response storage modulus of interest for the Dahlquist Criterion, overlap still exist and needs to be considered.

Given that the PSA is under relatively low strain during excitation in comparison to peel events, strict delamination is not typically a concern in application. On the opposite time spectrum from peel debonding, long term shear failure is a significant concern. Shear failure has been shown to be directly proportional to long term (low frequency) viscosity. Long term viscosity is related to the PSA rheology as $\lim_{\omega \to 0} \frac{\eta_2 G_2}{\omega}$ where ω is angular frequency [2], i.e. the long term loss modulus. As discussed, the composite loss factor is directly proportional to the viscoelastic material loss factor, η_2, in the frequency range and temperature of application. Hence, increasing the material damping is beneficial to composite performance. The increase in damping must be balanced against potential decreases in durability should the material loss factor be too high at low frequencies in the survivability temperature range of concern.

Durability associated with dissimilar coefficients of thermal expansion have shown particularly challenging for damping composite. Damping composites are typically installed at the interface between a controlled environment and a harsh environment such as the fuselage of an aircraft or body panel of a vehicle. Due to the location of installation and the varying substrates, survivability of large application temperature ranges, automotive applications exceed temperature spans of 120 C°, with thermal gradients through the damping material can cause significant COE concerns especially for different constraining layer and substrate situations. The end result is the potential for significant shear strain due to coefficient of thermal expansion. Conservative limits for shear strain which prevent failure in the PSA layer have been shown to be $\frac{\Delta L}{H_2} \leq 2$ where ΔL is the difference in length between the substrate and constraining layer and H_2 is the PSA thickness [8]. The limit in shear strain can be overcome by increasing the PSA thickness. However, increases in PSA thickness results in a decrease in peak composite damping performance within practical limitations.

Overall the constraints for using PSA as a damping material have practical constraints associated with use and durability. While the criteria for adhesion and damping are competing on several fronts, the presented discussion sets design new design windows for the application of PSAs as damping layers in constrained layer systems. The damping performance characteristics must be balanced with the adhesion characteristics which also vary with temperature and frequency.

5.0 Conclusion

A design study was presented for use with PSA as a damping layer in a composite. The study shows the advantages of using a damped constrained system in applications over extensions as a means to improve performance at reduced weights. Application specific design reviews show a meaningful range of frequency dependent modulus values of the PSA layer.

Further, a new approach to optimizing PSA design through the use of FE was presented. The new parameter enables the analysis of complex structures outside of simple idealized systems previously explored.

Finally design considerations for durability were contrasted against considerations for vibration damping performance. The design concerns for damping are often at odds for creating a durable PSA. Concerns with initial tack due to shifts in modulus performance and long term shearing are of concern.

6.0 Acknowledgements

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7.0 Citations

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