DESIGNING WITH WAVY COMPOSITES

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ABSTRACT

Wavy composite is a new form of constrained layer damping that uses standard fibers, resins, and viscoelastic materials to provide both high damping *and* stiffness. Wavy composites are used to build lightweight structures with high inherent damping, and stiffness. Originally conceived in 1990 by Dr. Benjamin Dolgin of NASA, a practical way of implementing this concept did not exist until 1997. During the period from 1997 to mid 2000 advances in FEA modeling and prediction, material selection, and testing, led to a number of important discoveries related to performance of these new materials that are covered in this article. Using damped wavy composites it is now possible to fabricate structures with the stiffness of steel, the weight of graphite composite, and unprecedented damping performance. Damping measurements as high as 30% with standard graphite fiber are reported. Unlike conventional constrained layer damping, wavy composites exhibit their exceptional damping qualities when excited by longitudinal, shear, and bending modes. While the performance of a given wavy composite structure is dependent on the properties of the viscoelastic used, it is possible to change the stiffness and damping response of the structure by varying materials, wave period, maximum angle, waveform, and thickness.

KEY WORDS: Advanced Composites, Analysis, Carbon Fiber, Characterization, Composite Materials, Composite Structures, Damping, Designing, Viscoelasticity

1. INTRODUCTION

Wavy composite is a new, and emerging form of constrained layer damping that uses standard fibers, resins, and viscoelastic materials in a new configuration to provide both high damping *and* stiffness. Originally conceived in 1990 by Dr. Benjamin Dolgin of NASA (Dolgin 1990), a practical way of implementing this concept did not exist until 1997 (Pratt 1999). During the period from 1997 to mid 2000 advances in FEA modeling and prediction, material selection, and testing, led to a number of important discoveries related to performance of this new material that are covered in this article. Dolgin's concept is shown in Figure 1.

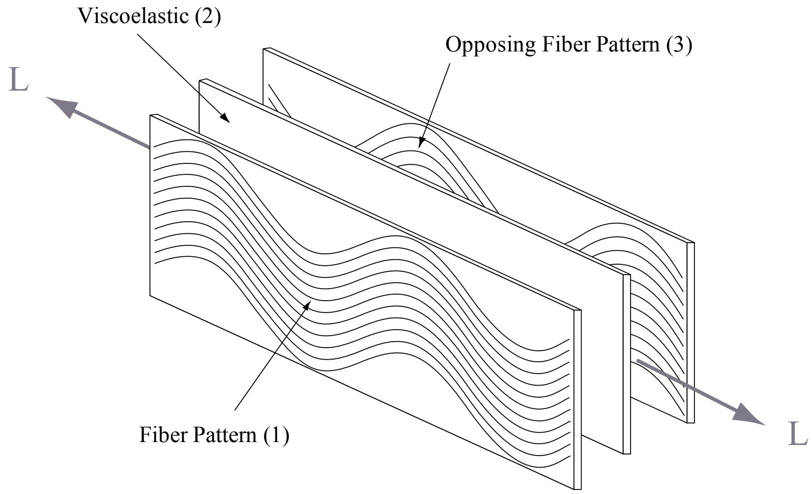


Figure 1: Basic damped wavy composite concept

Constrained Layer damping has been used to add damping to structures since 1950 (Kerwin 1959). Its most common form is the application of a thin tape of dead soft aluminum and viscoelastic adhesive. This method typically adds a few percent damping to the structure and there is little if any contribution to stiffness for the added weight of the constraining layer. Previous to the developments reported in this paper, higher levels of damping could only be accomplished at the expense of stiffness and/or strength (Bell, et al. 1996). Nevertheless, the potential weight advantage from the realization of higher damping, especially in aerospace structures (Liguore, et al. 1995), has driven the continued search for a practical means of adding structural damping.

In contrast wavy composites can be used to provide high levels of damping to structures without sacrificing stiffness, strength, or adding significant parasitic weight. Using damped wavy composites it is now possible to fabricate structures with the stiffness of steel, the weight of graphite composite, and unprecedented damping performance (30% has been measured, as high as 50% is predicted with high modulus fibers). Unlike conventional constrained layer damping, wavy composites exhibit their exceptional damping qualities when excited by longitudinal, shear, and bending loads.

The figures shown in this paper are model predictions generated by software developed by Patterned Fiber Composites, Inc. and verified experimentally by testing (Pratt, et al. 2001). Except where noted, all model results represent the axial stiffness and damping performance of damped wavy composite tubes fabricated from pre-preg made from Grafil 34-700 carbon fiber and a sports resin system, with a 60% ±1% fiber volume fraction. All waveforms used in this analysis were simple sinusoids defined by wavelength and maximum angle. The FEA model has been shown to give very good experimental correlation (less than 5% error in damping and stiffness predictions) and is based on the following assumptions.

1.1 Assumptions

1. Inherent damping and stiffness in the composite facesheet are independent of temperature and frequency over the useable range of the viscoelastic material (Adams, et al. 1969). This was experimentally verified using unidirectional pre-preg made at the same time as

the wavy composite material used in the fabrication of all samples. Typical values for damping in the fiber direction were 0.1 to 0.2 percent.

2. Linearly elastic modeling of stiffness and damping; small strain assumption. The assumption of small strains is used i.e. strain will be less than 1-2%. Strain greater than this usually involves failure in composites. This has shown to give very good agreement between model and actual test results (Pratt, et al. 2001).

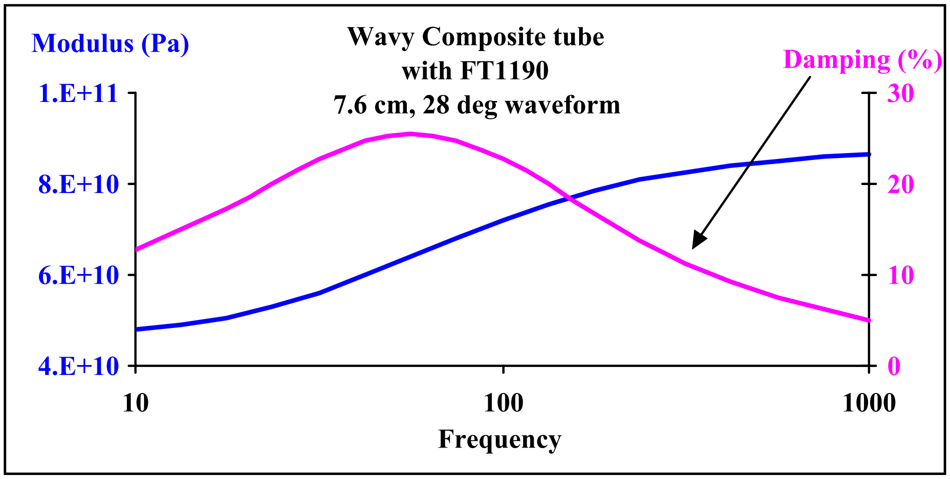
2. BASIC CONCEPTS

The following paragraphs detail the most important concepts that must be understood to execute good designs with wavy composites. They are:

- The viscoelastic layer dominates the damping and stiffness performance of a wavy composite combination. As a result, all the concepts that apply for a linear viscoelastic material apply to the combination of wavy composite and viscoelastic material, namely:
    1. Wavy composites exhibit glass transitional properties, i.e. there are defined asymptotic values for stiffness, and a defined damping peak as a function of temperature and frequency.
    2. Frequency-temperature superposition, i.e. a change in temperature is equivalent to a change in frequency (Ferry 1980).
    3. Viscoelasticity, i.e. damping can be approximated by factoring the modulus or stiffness of a material.
- Damping and stiffness in wavy composites can be tailored to the dynamics of the structure. Although the wavelength, maximum angle, thickness ratios of constraining to constrained layer, fiber type, and temperature, all combine to effect the location and magnitude of the damping peak (and the stiffness), in general, the following is true for a given viscoelastic at a constant temperature:
    1. The frequency of peak damping in a wavy composite structure is primarily driven by the wavelength.
    2. The magnitude of the damping peak and the stiffness are driven by the maximum angle of the waveform. It should be noted that the stiffness reported is based on the equivalent axial stiffness (stiffness in the strong direction) of load bearing material without the viscoelastic, i.e. stiffness does not include the volume of the viscoelastic material. This is normal for conventional constrained layer damping where the constraining layers of dead soft aluminum and viscoelastic adhesive are not considered in the determination of stiffness of the structure. This is done to provide a basis for comparison of the material characteristics of the composite.

2.1 Characteristics of wavy composites

The viscoelastic layer dominates the damping and stiffness performance of a wavy composite combination. Comparison of the modulus and damping of the wavy composite – viscoelastic combination in Figure 2 (upper chart) and the viscoelastic (only) in Figure 2 (lower chart) shows the shape of the curves to be similar in every respect. As is typical for a viscoelastic material, for wavy composite combinations there is a defined damping peak that coincides with the glass transition temperature of the material, and a shear modulus that has a lower and upper asymptote.



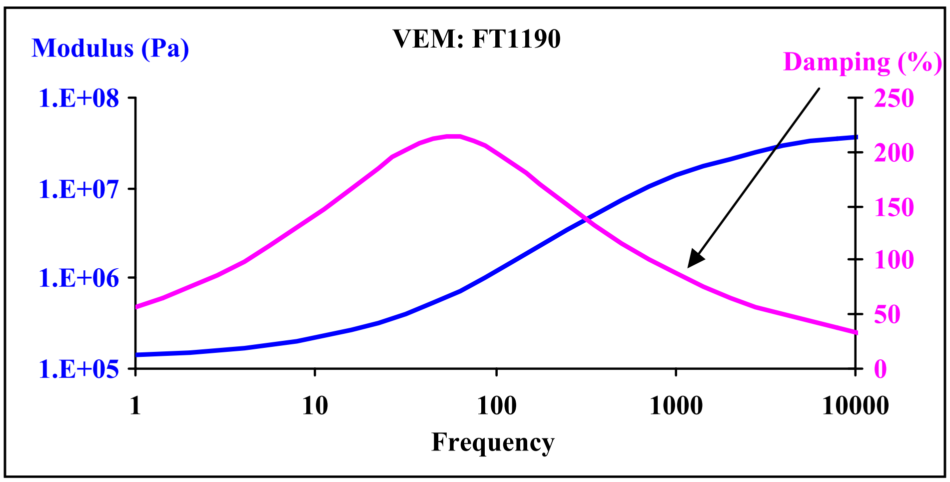


Figure 2: Modulus and damping of wavy composite tube made with FT1190 VEM (upper chart) compared with FT1190 series viscoelastic properties at 25° C (lower chart).

While the performance of wavy composite is dependent on the properties of the viscoelastic used, the ability to change the stiffness and damping response of the structure by varying the waveform gives the designer significant latitude to pursue optimal designs. For example, the charts in Figure 3 and Figure 4 (room temperature response), show the damping and modulus for five different wavelengths where thickness, and maximum angle (of the sinusoidal waveform) are held constant.

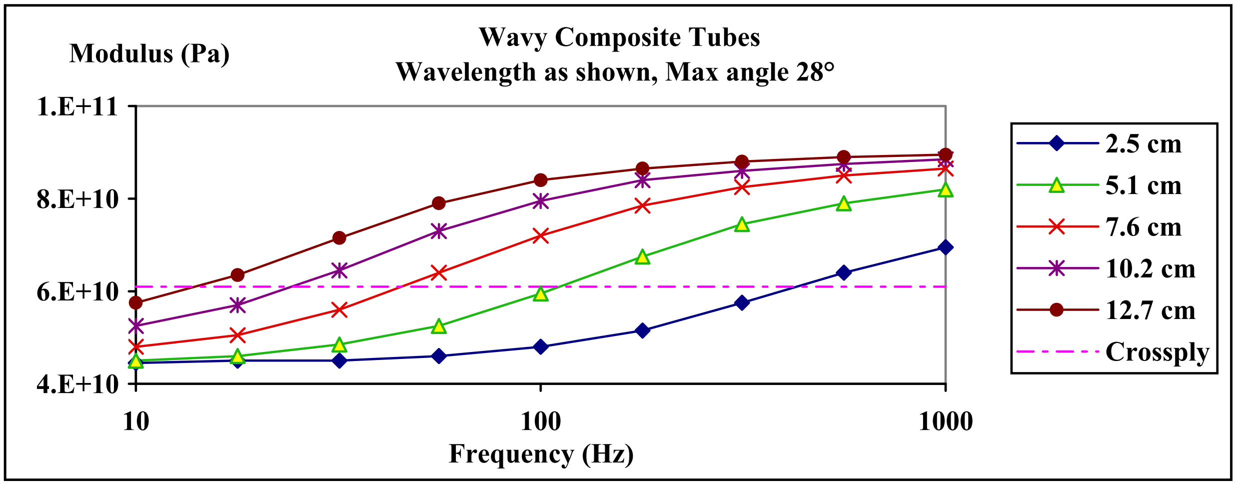


Figure 3: Equivalent axial modulus for carbon fiber wavy composite – viscoelastic tube.

The curves shown in Figure 3 represent the equivalent axial modulus as a function of frequency at room temperature. As can be seen, there are asymptotic values for the modulus of the wavy composite – viscoelastic structure that are attributable to the stiffness characteristics of the viscoelastic material. For reference, the stiffness of aluminum is approximately 68 GPa; the 0 degree properties for carbon composite material is 180 GPa; and a unidirectional crossply lay-up (shown as "Crossply" on both figures) of the same maximum angle would have a stiffness of 61 GPa but a damping performance of only 1.5%.

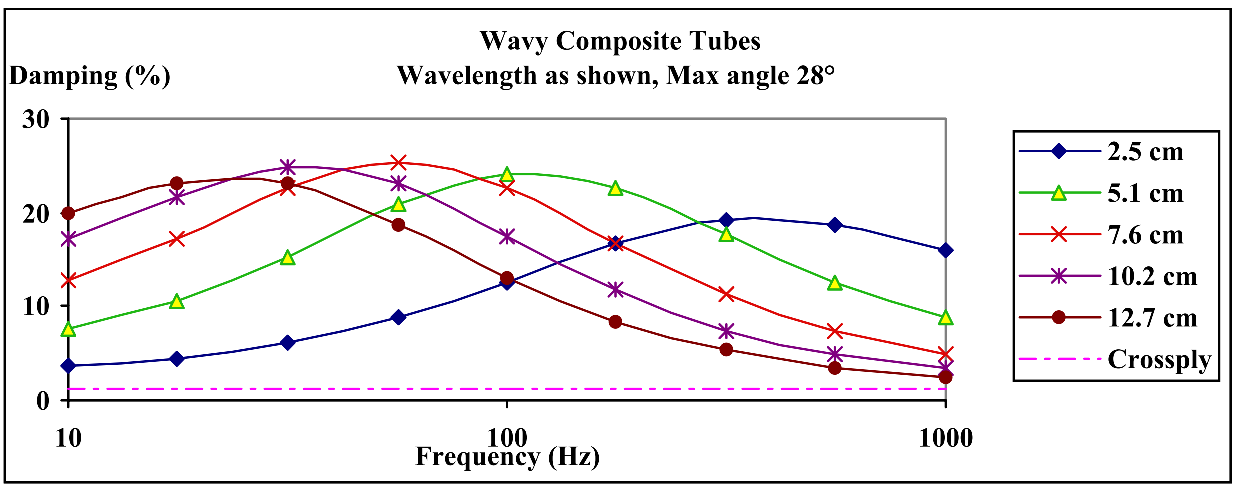


Figure 4: Damping (%) performance for carbon fiber wavy composite – viscoelastic tube.

Note in Figure 4 that the damping peak varies for the different waveforms and like the modulus, mirrors the shape of the viscoelastic material in every case. In Figure 4, the 7.6 cm period waveform produces the highest damping at the frequency (60 hertz) that coincides with the peak damping frequency of the viscoelastic. The fact that damping peaks for the 2.5, 5.1, 10.2, and 12.7 cm waveforms are lower than the 7.6 cm waveform is probably due to a less than optimal combination of viscoelastic modulus and loss factor. Despite this, appropriate selection of wave period can still provide high damping and provides greater design flexibility.

Using both figures, the designer has the option to maximize damping, or optimize the stiffness of the structure for a certain frequency band of interest by changing the wavelength of the sinusoidal wave. For example, if the frequency band of interest lies between 100 and 1000 hertz, the designer could select a waveform with a period of from 2.5 to 5.1 cm depending on the stiffness and damping desired. A 5.1 cm waveform would give a stiffer response and provide greater damping at lower frequencies. Thus the following is true:

> **Design principle 1: For a given temperature, the wavelength of a wavy composite structure determines the frequency of the damping peak for a given viscoelastic material.**

In a sinusoidal waveform, a change in angle will alter both the stiffness and damping. Figure 5 shows the effects of varying the maximum angle of the sinusoid for a sample tube made from standard graphite fiber wavy composite with a 7.6 cm wave period. If stiffness is emphasized more than damping, the designer can decrease the maximum angle and dramatically improve the stiffness of the wavy composite. For reference, the stiffness of aluminum would be 69 GPa, and titanium would be 110 GPa. Thus, it is possible to use a 20° - 7.6 cm sinusoidal pattern to create a capable substitute for aluminum with orders of magnitude greater damping. Figure 5 only represents one of the waveforms shown in Figure 3 and Figure 4. Changing the maximum angle and wave period provides the designer with the ability to optimize the structural response for a wide variety of conditions.

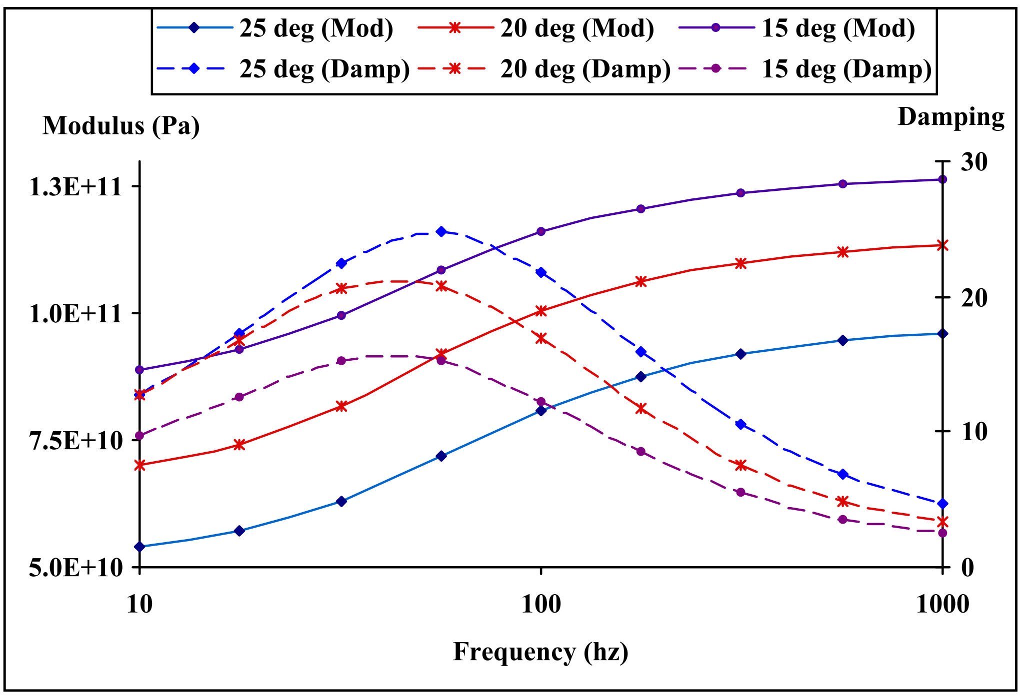


Figure 5: Effects of a change in angle for a sinusoidal waveform of a 7.6 cm wavelength.

> **Design principle 2: For a given temperature, the maximum angle of the waveform determines the magnitude of damping and stiffness for a given viscoelastic material.**

Although not shown, nomograph charts can be used to predict the performance of this material combination at different temperatures as is typically done for viscoelastic materials. The x-axis represents not only the frequency scale at room temperature but also represents the reduced frequency scale of a frequency-temperature nomograph. To complete the chart as a nomograph, the designer would have to add another frequency scale on the vertical axis and isothermal lines using the WLF equations (Ferry 1980). Similar charts can be generated for the effects of amplitude-to-wavelength ratio (or maximum angle in the case of a sinusoidal waveform), thickness ratios, in nomograph form. The following illustrates the principle of time-temperature superposition.

2.2 Time-temperature superposition

Figure 6 shows the frequency shift of the stiffness curve due to changes in temperatures for a given waveform. The principle of polymer frequency-temperature superposition states that a shift in frequency is equivalent to a shift in temperature and is the method by which a master curve or nomograph is obtained (Ferry 1980). This principle is true for wavy composites made with polymer viscoelastic layers.

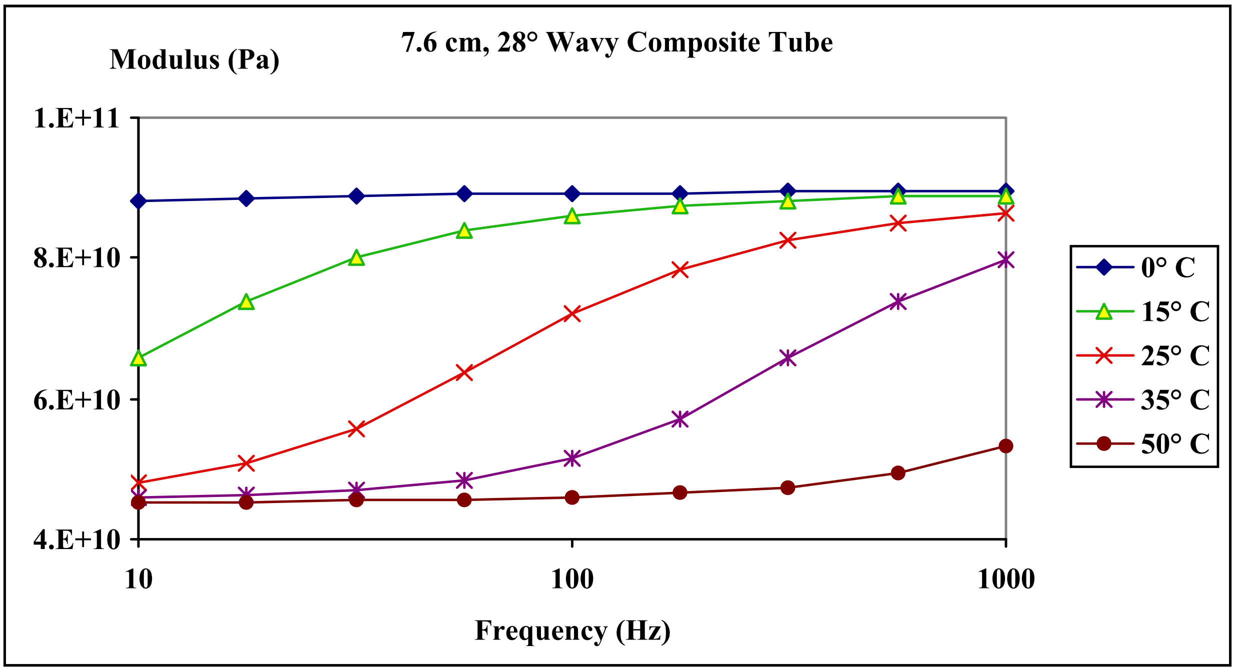


Figure 6: Frequency shift of the stiffness curve due to temperature.

Figure 7 illustrates the corresponding shift in the damping curves for the same lay-up. As can be seen, the frequency shift of the damping peak is dramatic for a relatively small shift in temperature for this viscoelastic. The peak value, however, does not change as a function of temperature, only the *frequency* of the damping peak changes.

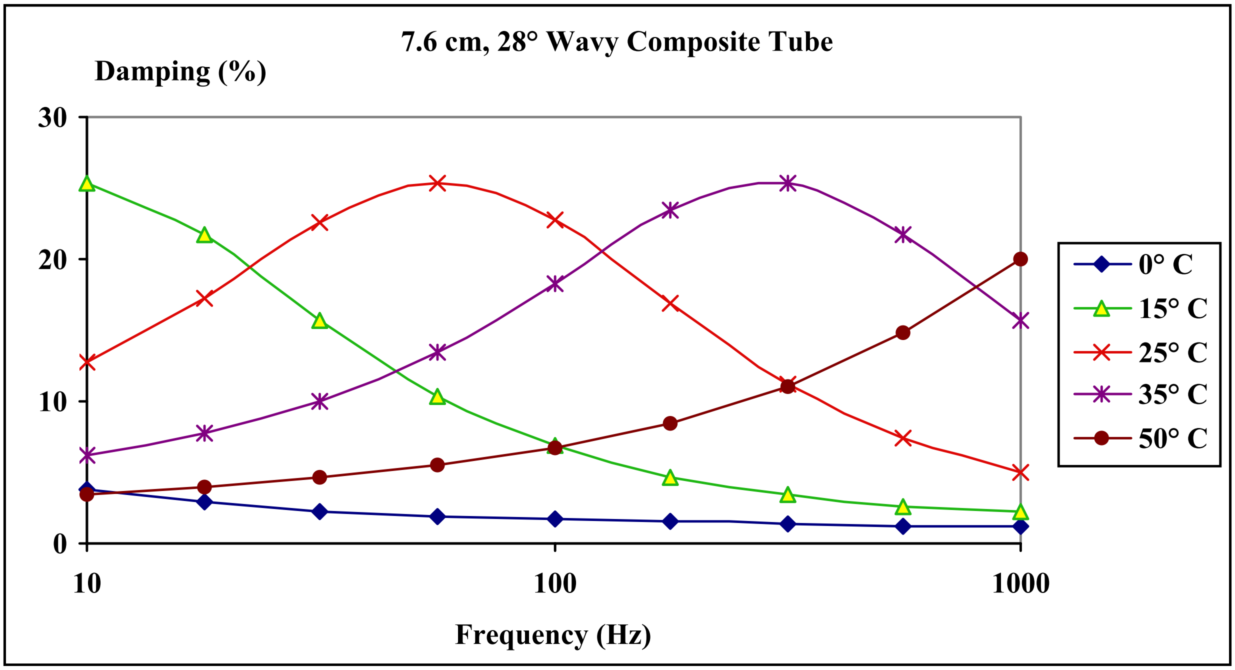


Figure 7: Shift in damping peak due to changes in temperature

This particular viscoelastic material has a narrow glass transition zone. This gives a sharp peak to the damping curve but is used for these illustrations primarily because it has been tested and correlated to our FEA model with less than 5% error in both damping and stiffness predictions.

> **Design principle 3: For wavy composites, a change in temperature is equivalent to a change in frequency and a master nomograph can be established using the WLF equation.**

2.3 Thickness ratio effects

Changing the thickness of the constraining layer or the viscoelastic layer in a wavy composite has the same effect on stiffness or damping as a minor temperature change, for reasonable thickness ratios. To illustrate this point refer to Figure 8 which shows the effects of changes in the thickness of constraining composite layers or viscoelastic layers on the stiffness of a damped wavy composite laminate composed of two composite facesheets and one viscoelastic layer. The baseline configuration is a wavy laminate with 0.25mm thick composite facesheets with a 7.6 cm, 24 degree sinusoidal waveform, and a 0.2mm thick viscoelastic layer.

If the composite facesheets are doubled in thickness, the effect is the same as if the viscoelastic layer was doubled in thickness. Both cause a shift in the frequency of the curve similar to a small temperature shift.

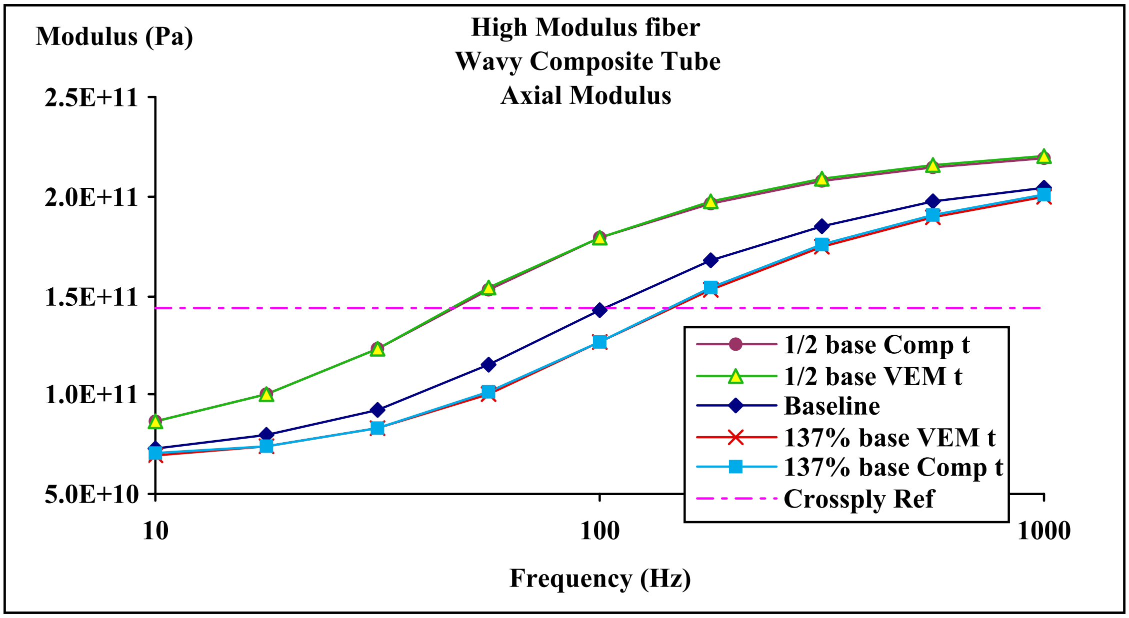


Figure 8: Effects of changing thickness of composite or viscoelastic layers on stiffness.

Figure 9 represents the effects of changes in thickness on the frequency of the damping peak of the laminate. Like the stiffness, a change in the thickness of either composite or viscoelastic while holding the other material's thickness constant produces the same result. The effects of changing thickness are additive; changing both VEM and composite thickness will shift the frequency scale even more. Similar to the change in wavelength (Figure 4), as the damping peak moves away from the peak performance of the viscoelastic layer (see Figure 2) the magnitude of the damping peak will diminish slightly.

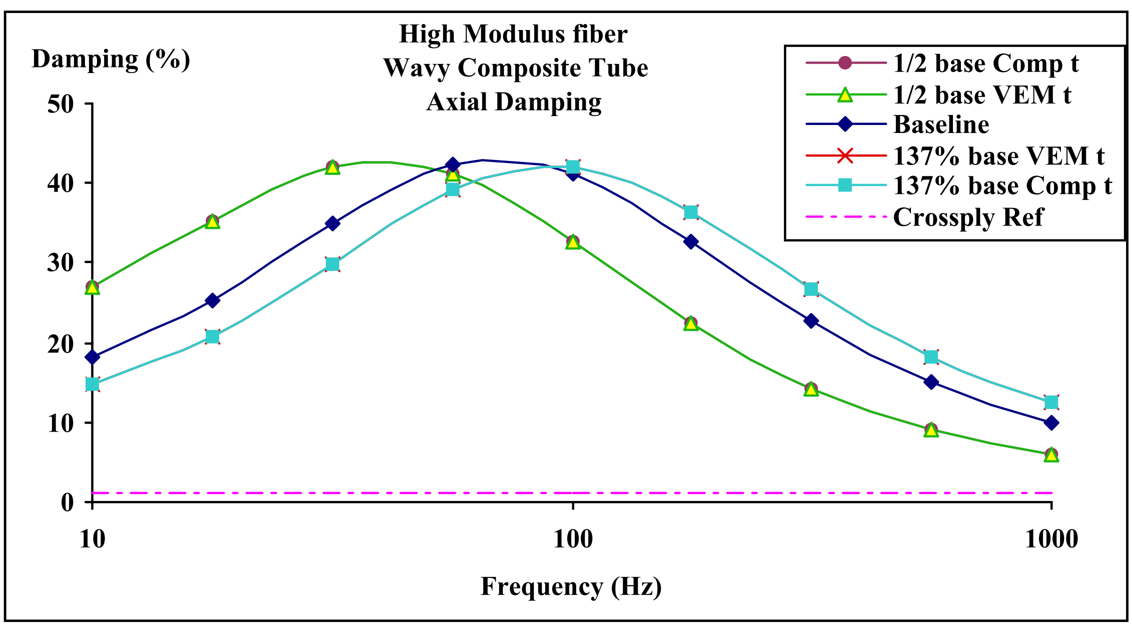


Figure 9: Effects of changing thickness of composite or viscoelastic layers on damping.

It is evident from these figures that thickness ratios have an effect, albeit a minor one, on the frequency of peak damping for a given temperature for reasonable values of thickness. What is meant by reasonable values? Experience to-date has shown that ratios of approximately 1:3 to 3:1 with a baseline thickness of approximately .25 mm give the best overall performance.

> **Design principle 4: For a given waveform, a change in thickness ratios of viscoelastic or wavy composite will shift the damping and stiffness "master" curves similar to a small change in temperature. Increasing the thickness of either viscoelastic or wavy composite layer shifts the damping peak to a higher frequency; decreasing the thickness of either viscoelastic or wavy composite layer shifts the damping peak to a lower frequency. Effects are additive although not linearly.**

2.4 Increasing performance in wavy composites

To this point in this paper, figures and discussion have centered on examples of wavy composites designed to produce maximum damping performance. If greater emphasis is given to stiffness, there are a number of methods whereby stiffness can be increased with little adverse effect on damping performance. The obvious method of increasing stiffness in a sinusoidal waveform, is to reduce the maximum angle as shown in Figure 5.

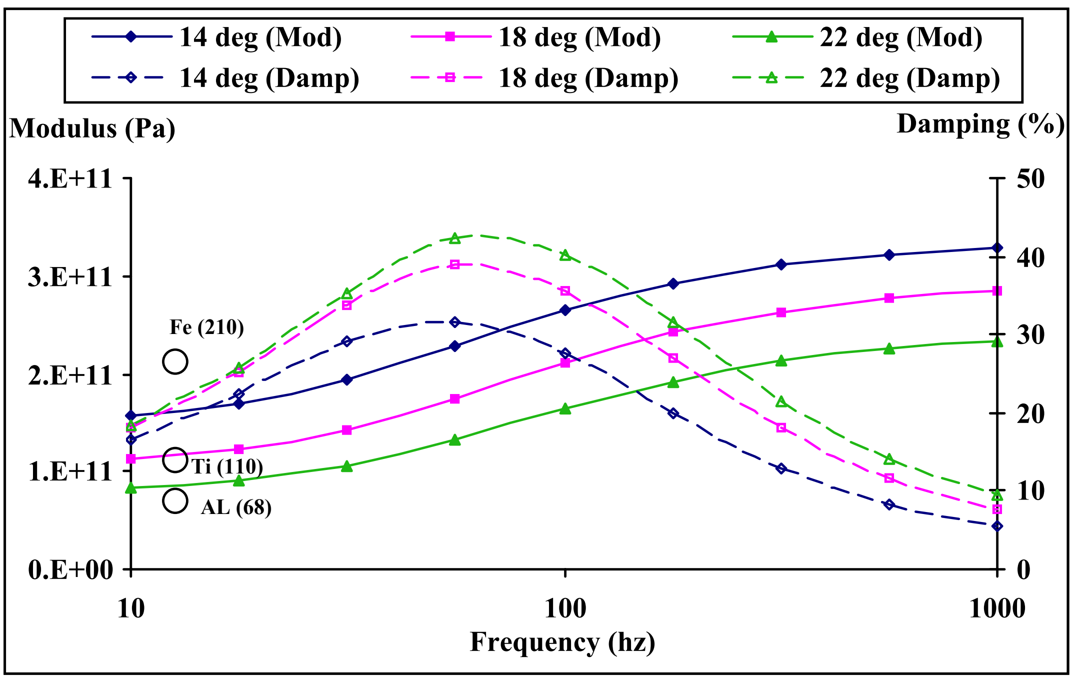


Figure 10: High modulus fiber based wavy composite tube axial modulus and damping performance at different maximum angles, wavelength 7.6 cm

It is also possible to use stiffer fibers in the wavy constraining layers. Figure 10 shows the stiffness and damping performance of three different angles of a 7.6 cm wavelength, using Mitsubishi's K13710 high modulus fiber. For reference, the stiffness of titanium is approximately 110 GPa, and the stiffness of steel is approximately 210 GPa. When compared to Figure 5 it is immediately obvious that stiffer wavy constraining layers will give both improved damping *and* stiffness. This is shown in Figure 11 where maximization of damping is the main design criteria.

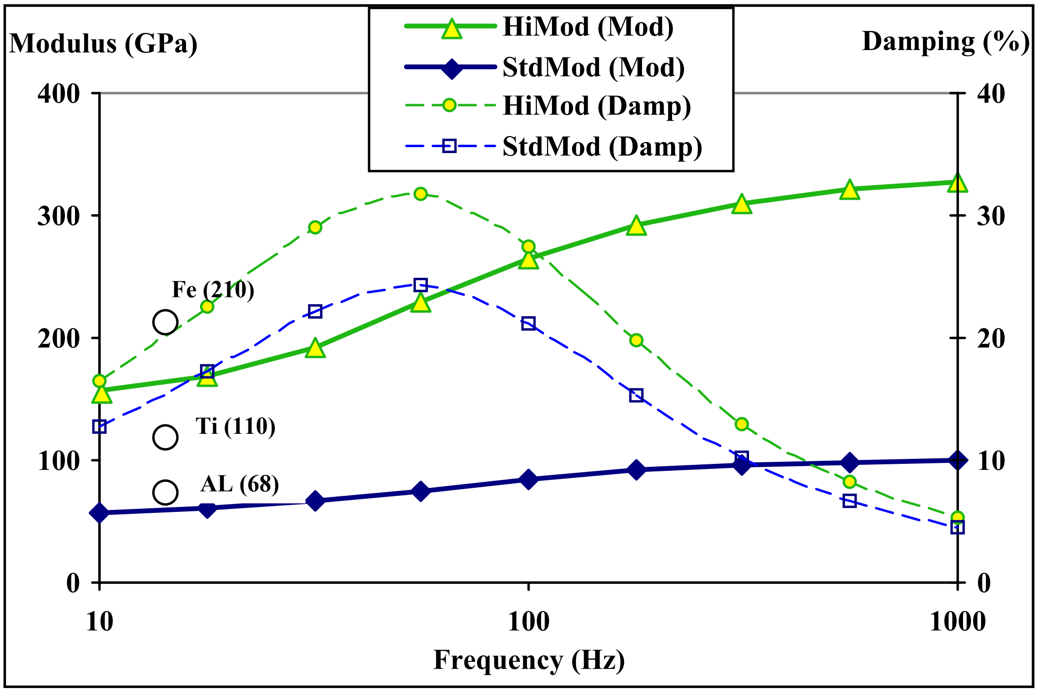


Figure 11: Comparison between high modulus fiber (K13710) and standard carbon fibers.

> **Design principle 5: The use of higher modulus fibers in the wavy constraining layers will give higher damping and stiffness.**

There are other methods of increasing stiffness in wavy composite based structures including the use of conventional composite materials to provide the primary load resisting capability, and use of wavy composite-viscoelastic combinations primarily for damping treatment. Since the wavy composite portion of a mixed composite structure provides significant stiffness in addition to damping, careful design and analysis should be accomplished to optimize the damping, stiffness, and weight. These and other issues will be covered in future papers.

3. DESIGNING WITH WAVY COMPOSITES

Given the five design principles developed in this paper, how does one design with this new material? The short answer is: "just like any other composite." It handles the same, it has very predictable properties, and like the use of any composite, requires a careful assessment of the "design space/objectives." The primary difference in the use of this material is that the designer must establish a set of dynamic goals to be met by the structure. Instead of determining only the static loading conditions, safety factor, and fatigue considerations, the designer must add considerations of frequency of the loads or offending vibrations, the range and level of damping required, and the operating temperature range.

An example will illustrate the use and capability of this new material. The application is an interior panel for an executive aircraft. The temperature range is 21° ±3° C. The frequency range of interest is 100 to 4000 Hz. It was desired to cause peak damping in the panel to occur at the first bending mode (180 Hz). The structure is a foam core beam measuring 11.5 cm by 61 cm by 1.3 cm thick.

Damping will provide a major benefit where the majority of acoustic excitations are caused by non-diffuse, acoustic standing waves, and mechanically excited vibrations of the aircraft that couple efficiently to the cabin. In this case, added stiffness *and* damping are appropriate solution methods for attenuating sound pressures in the cabin (Norton 1996).

Two panels of comparable stiffness were tested and damping performance was determined by using the half power method at several different temperatures (to obtain a "master curve"). Results are plotted in Figure 12. The "undamped" panel is a conventional composite beam where the facesheets are constructed of six layers of ±30° unidirectional composite in a balanced crossply design. The wavy panel uses six layers of wavy composite in each facesheet with a viscoelastic damping layer interposed between three-layer opposing waves in the same configuration of Figure 1. The waveform has a wavelength of 4 cm and a maximum angle of 30°. In both the undamped and wavy panels, the facesheets were bonded directly to the foam core. Peak damping for the wavy composite panel was 30% whereas the undamped panel exhibited only two to three percent damping.

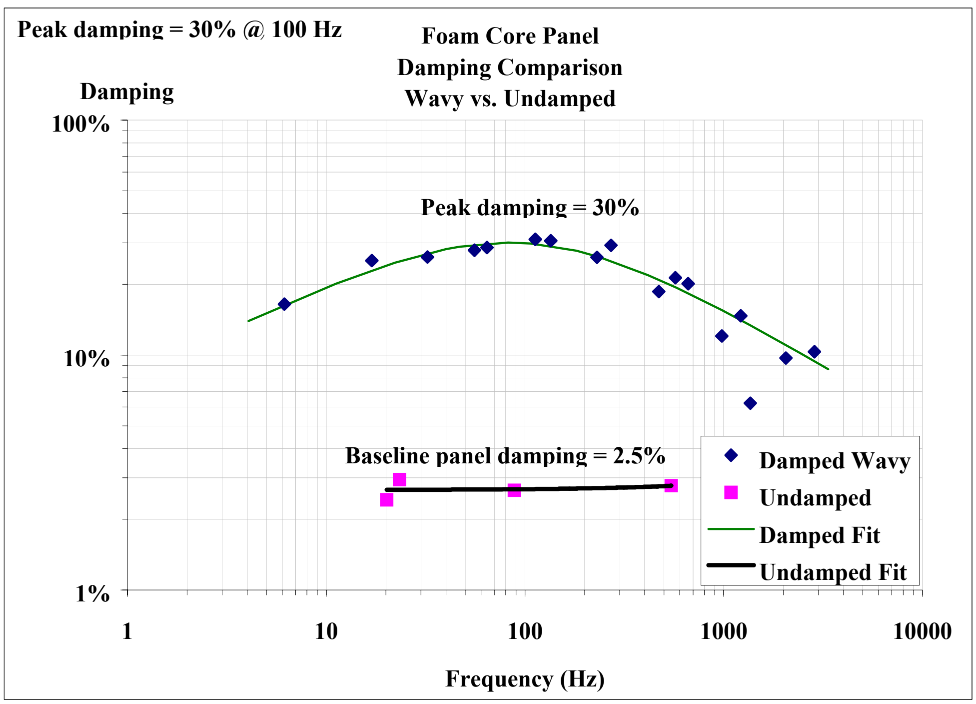


Figure 12: Test data showing damping measurements of wavy damped panel vs. equivalent undamped panel.

The choice of waveform was made to cause the damping in the panel to peak at the first bending mode of the panel. The frequency of the first three bending modes was 180, 510, 950 Hz with damping at these modes of 28%, 20%, and 16% respectively. One need not use FEA analysis to determine the optimal waveform for the structure. If the first bending resonance can be approximated, the correct waveform can be selected from nomographs for the material (similar to Figure 4) and the design completed.

4. SIGNIFICANCE

The five design principles that have been developed in this paper have been applied to a number of practical designs including panels, golf club shafts, skis, and a number of basic shapes such as tubes, and flat plates. In every case, optimal performance was accomplished using careful selection of waveform to achieve the desired effect.

"Smart" composite structures have a myriad of potential applications and uses for aerospace vehicles including space trusses, missiles, satellites, airframes, interior panels, enclosures and launch containers, and in general any assembly where structural damping and acoustic attenuation is important. The following is quoted from the 2000 National Space & Missile Materials Symposium introduction:

> "Revolutionary materials technology is critical and will take a generation or more to achieve. Materials are the enablers for next generation, affordable and safe reusable launch systems, advanced spacecraft, and payloads…."

Patterned Fiber Composites, Inc. feels that one of the next generation materials (and capable analysis software) are available for immediate use and are being applied to a growing number of practical applications, with a widening group of industrial clients.

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