Investigation of High and Negative Poisson’s Ratio Laminates

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ABSTRACT

Fiber-reinforced elastomer composites are receiving increased attention because of their abilities to undergo large elastic deformation, reduce vibration, and absorb high shock loads. Additional applications may be possible because of the highly orthotropic nature of fiber-reinforced elastomers (elastomer composites). It is well known that the maximum Poisson’s ratio for isotropic materials is 0.5 as found in elastomeric incompressible materials. However, it is easily shown that Poisson’s ratios twice unity can be obtained with a graphite/epoxy angle-ply laminate at about 25°. Chou predicted Poisson’s ratios as high as 7 for certain elastomer composite combinations. Peel used four experimentally obtained material combinations to show Poisson’s ratios as high as 32. However the very nature of high Poisson’s ratios caused specimen gripping and testing problems. In the current work, preliminary experimental results have produced Poisson’s ratios as high as 14, and results from new configurations are predicted to be as high as 100. Certain combinations of highly orthotropic lamina, stacking sequences, and orientations may also produce laminates that exhibit negative Poisson’s ratios less than -60. If experimentally verified, these laminates may significantly increase damping and enable a new category of solid-state actuators and actuated compliant mechanisms suitable for micro- and nano-structures.

KEY WORDS: Advanced Composite Materials, Materials – Elastomer/Rubber, Mechanical/Physical Properties

1.0 INTRODUCTION

Advanced composite materials, typically consisting of carbon, fiberglass, or glass fibers, embedded in an epoxy or polyester matrix, are widely used because of their ability to provide high strength and stiffness at densities lower than common metals. One advantage of fibrous structures is the ability to tailor strength and/or stiffness along a particular load path or in a certain direction. Elastic tailoring, where the behavior of a structure, such as a wing, is also much easier with composites, than with metals. For example, the forward-swept wings of NASA’s X-29 had laminates oriented such that as they became highly loaded, and deflected upward, the camber of outer sections would decrease. This tended to unload the wing slightly, and delay stall. Taking “tailoring” to an “active” realm, sensors and actuators are now being
embedded in composite structures, allowing them, with their associated analysis and control support, to be considered “smart” or “adaptive” structures.

The ratio of axial to transverse stiffness for elastomer matrix composites is much greater than for traditional aerospace composites. This may lead to the ability to obtain passive or active structural responses not currently possible with traditional composites. Non-calendared (other than tires and belting) fiber-reinforced elastomer (FRE) or flexible composites are also receiving interest for use in vibration damping, impact resistance, and as actuators. Typical FREs or elastomer composites consist of fiberglass, carbon, and Kevlar, embedded in an elastomeric matrix. The most common matrices are polyurethanes or silicones. Polyurethanes are especially useful because they bond well to the standard sizings or coatings on aerospace fibers. Silicones require special fiber sizing treatments, but withstand higher temperatures than polyurethanes and tend to stiffen rather than soften when initially stretched [1].

The current work investigates the Poisson’s ratio of solid (non-foam, non-segmented) laminates fabricated from FREs. High Poisson’s ratio laminates; negative Poisson’s ratio (auxetic) laminates, and simple applications will be explored. High and negative Poisson’s ratio laminates have the capability to increase damping, allow additional elastic responses, may enable new classes of micro-actuators, and facilitate new types of fasteners.

2.0 LITERATURE SURVEY

Limited literature is available on solid composite materials having high or negative Poisson’s ratios. Most works define high Poisson’s ratios as those close to 0.5. Most negative Poisson’s ratios or auxetic references deal with foam-like structures.

Clark [2] predicted inplane Poisson’s ratios as high as 7 for certain cord-rubber laminates. His experimental results compared quite well and showed that Poisson’s ratio is a function of angle for angle-ply laminates. Chou [3] states, “It is evident that Poisson’s ratios well in excess of one-half exist in cord-rubber composites.” Using data from Akasaka [4] Chou shows out of plane or $v_{xz}$ ratios in excess of –2. Peel [5] used four experimentally obtained FRE material combinations to predict Poisson’s ratios as high as 32. Ruguang and Yeh produced very small negative ratios using traditional composite materials [6].

Lakes, Lee, Evans, Alderson, and others in quite extensive works, have simulated and developed foams that exhibit negative Poisson’s ratios and Poisson’s ratios greater than 1 [7-9]. Scarpa and Tomlinson [10] show that aluminum sandwich panels with auxetic cores will damp vibration better than those with traditional honeycomb cores.

Based on their work with auxetic foams, Alderson et. al. have developed auxetic polypropylene fibers that could have uses in fasteners, gaskets, and where fracture toughness is needed [11]. In a very recent work, Evans, Donoghue, and Alderson, have developed software that will allow a designer to match auxetic and traditional carbon fiber laminates [12]. In a concurrent work, Keshavamurthy, Hossakere and the author show that non-optimized FRE laminates that exhibit high and negative Poisson’s ratios produce damping greater than traditional orthotropic FRE laminates [13].

Material properties for selected fiber-reinforced elastomer, traditional composite, and isotropic materials of interest are presented in Table 1. They will be used in the following simulations. All FRE axial and transverse stiffnesses presented in Table 1 are considered initial values. The
author, in reference [14], presents coefficients for a nonlinear Ogden model of Fiberglass/RP6410 and Fiberglass/Silicone.

| Material                  | $V_f$ (%) | $E_1$ (MPa, psi) | $E_2$ (MPa, psi) | $
u_{12}$ | $G_{12}$ (MPa, psi) |
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Fiberglass/RP6410</td>
<td>17.9</td>
<td>12,960 (1.88E+6)</td>
<td>2.25 (327)</td>
<td>0.45</td>
<td>5.34 (774)</td>
</tr>
<tr>
<td>Fiberglass/Silicone</td>
<td>12.1</td>
<td>8,761 (1.27E+6)</td>
<td>1.94 (282)</td>
<td>0.47</td>
<td>1.95 (283)</td>
</tr>
<tr>
<td>Graphite/RP6410*</td>
<td>42.1</td>
<td>122,000 (17.6E+6)</td>
<td>2.85 (413)</td>
<td>0.41</td>
<td>0.949 (138)</td>
</tr>
<tr>
<td>Graphite/RP6442*</td>
<td>41.8</td>
<td>126,600 (18.4E+6)</td>
<td>12.02 (1743)</td>
<td>0.41</td>
<td>4.00 (580)</td>
</tr>
<tr>
<td>IM7/8551-7a**</td>
<td>54</td>
<td>145,000 (21.0E+6)</td>
<td>8,825 (1.28E+6)</td>
<td>0.36</td>
<td>4895 (7.1E+5)</td>
</tr>
<tr>
<td>RP6410 Urethane#</td>
<td>-</td>
<td>1.65 (239)</td>
<td>-</td>
<td>0.50</td>
<td>0.549 (79.6)</td>
</tr>
<tr>
<td>Nitinol SMA#</td>
<td>-</td>
<td>58.6 (8.5E+6)</td>
<td>-</td>
<td>0.33</td>
<td>22.06 (3.2E+6)</td>
</tr>
</tbody>
</table>

* Obtained using Rule of Mixtures [13]. ** Reference [15]. # Reference [16]

3.0 THEORETICAL DEVELOPMENT

3.1 Poisson’s Ratios for Isotropic Materials To aid the understanding of Poisson’s ratios (PR), a review of fundamental concepts is in order. We learn in Continuum Mechanics [17] that the sum of the three orthotropic components of linear strain for a small element of continuous material, or

$$\varepsilon_x + \varepsilon_y + \varepsilon_z = a$$  \hspace{1cm} (1)

is invariant, that is, $a$ is constant no matter the orientation of the orthogonal $xyz$ coordinate system. This is true for anisotropic as well as isotropic materials. If we divide both sides of equation 1 by $\varepsilon_x$, we get

$$1 + \frac{\varepsilon_y}{\varepsilon_x} + \frac{\varepsilon_z}{\varepsilon_x} = \frac{a}{\varepsilon_x} = b$$ \hspace{1cm} (2)

where we have defined $b = a/\varepsilon_x$ for convenience. Remembering the definition of PR, we write equation 2 as

$$1 - \nu_{xy} - \nu_{xz} = b.$$ \hspace{1cm} (3)

For incompressible materials such as rubber and water, where the bulk modulus $K$ is close to infinity, $a = 0$, so $b = 0$ as well. If the material is isotropic as well, then $\nu_{xy} = \nu_{xz} = \nu$. Solving
for \( \nu \) we find that it equals 0.5, exactly as predicted. If we assume that as we strain the element of material by an amount \( c \), in the \( x \) direction, and find that it expands by the same strain \( c \) in the \( y \) and \( z \) directions, we will obtain a PR of \( \nu = -1 \). However, our little word exercise does not preclude the element of material from deforming in another manner, so we have not proved that \( \nu = -1 \) is a lower limit.

The two elastic LamP constants, \( \lambda \) and \( \mu \), as introduced by LamP in 1852 for isotropic materials, are related to the better known shear modulus \( G \), Young’s modulus \( E \), and \( \nu \), by the equations

\[
\mu = G = \frac{E}{2(1 + \nu)} \quad \text{and} \quad \lambda = \frac{\nu E}{(1 + \nu)(1 - 2\nu)}.
\]

Assuming that \( \lambda \), as defined in equation 4, is always positive, and if we assume that \( E \) is greater than zero, then \( \nu \) must be greater than \(-1\) and less than 0.5 for isotropic materials.

Revisiting equations 2 and 3, we can see that for non-isotropic materials, one PR could have a very large positive or negative value, if counteracted by the other, or by the total cubical dilatation \( a \). This may also mean that for a laminate, it is possible that one could have a large positive inplane PR (\( \nu_{xy} \)), but as a result, either the axial strain (\( \varepsilon_x \)) must be very small, or the thickness-direction ratio (\( \nu_{xz} \)) may be negative. The current work considers only the prediction of the inplane ratio \( \nu_{xy} \).

### 3.2 Overview of Classical Lamination Theory (CLT)

CLT assumes that strains are small and orthotropic material properties are linear. Cord-rubber composites and FREs used in structural applications typically experience strains less than 10%. They have fairly linear stress-strain relationships over that range, hence CLT is adequate. Although FRE materials can experience large strains, and produce nonlinear stress-strain responses, that work is beyond the scope of this article but is considered in another work by the author [14]. This work uses the orthotropic material properties \( E_1, E_2, G_{12}, \) and \( \nu_{12} \) to describe the inplane axial modulus of elasticity, inplane transverse modulus of elasticity, inplane shear stiffness, and inplane major PR, respectively, in each layer of a laminate. From these properties, the reduced stiffnesses, \( Q_{ij} \), can be found:

\[
\frac{V_{12}}{E_i} = \frac{V_{21}}{E_j} \quad (5)
\]

\[
Q_{11} = \frac{E_1}{1 - \nu_{12}V_{21}} \quad (6)
\]

\[
Q_{12} = \frac{\nu_{12}E_2}{1 - \nu_{12}V_{21}} \quad (7)
\]

\[
Q_{22} = \frac{E_2}{1 - \nu_{12}V_{21}} \quad (8)
\]

\[
Q_{66} = G_{12} \quad (9)
\]

\[
Q_{16} = Q_{26} = 0 \quad (10)
\]

These \( Q_{ij} \)'s are reduced stiffness values and can be combined in a matrix form to find the stresses in an orthotropic layer:
An orthotropic lamina can have its principle material axes rotated from global coordinate system to a local orientation \( \theta \) as shown in Figure 1. Stresses and strains can be easily transformed from one set of axes to another as shown in equation 12:

\[
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{bmatrix} = \begin{bmatrix}
\cos^2 \theta & \sin^2 \theta & -2 \sin \theta \cos \theta \\
\sin^2 \theta & \cos^2 \theta & 2 \sin \theta \cos \theta \\
-2 \sin \theta \cos \theta & 2 \sin \theta \cos \theta & \cos^2 \theta - \sin^2 \theta
\end{bmatrix} \begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_{12}
\end{bmatrix}
\] (12)

Figure 1  Coordinate systems for laminate and layer axes.

If the elastic constants \( \bar{Q}_{ij} \) are rotated to the global coordinate system, the transformed stiffness can be found:

\[
\begin{align*}
\bar{Q}_{11} &= Q_{11} \cos^4 \theta + 2(Q_{12} + 2Q_{16}) \sin^2 \theta \cos^2 \theta + Q_{22} \sin^2 \theta \\
\bar{Q}_{12} &= (Q_{11} + 4Q_{66}) \sin^2 \theta \cos^2 \theta + Q_{12} (\cos^4 \theta + \sin^4 \theta) \\
\bar{Q}_{22} &= Q_{11} \sin^4 \theta + 2(Q_{12} + 2Q_{66}) \sin^2 \theta \cos^2 \theta + Q_{22} \cos^4 \theta \\
\bar{Q}_{16} &= (Q_{11} - Q_{22} - 2Q_{66}) \sin \theta \cos^3 \theta + (Q_{12} - Q_{22} + 2Q_{66}) \sin^3 \theta \cos \theta \\
\bar{Q}_{26} &= (Q_{11} - Q_{22} - 2Q_{66}) \sin^3 \theta \cos \theta + (Q_{12} - Q_{22} + 2Q_{66}) \sin \theta \cos^3 \theta \\
\bar{Q}_{66} &= (Q_{11} + Q_{22} - 2Q_{16}) \sin^2 \theta \cos^2 \theta + Q_{66} (\cos^4 \theta + \sin^4 \theta)
\end{align*}
\] (13-18)

Chou has suggested alternate forms for the transformed stiffnesses, when \( E_1 \gg E_2 \) [3]. The advantage of these terms is that all \( \bar{Q}_{ij} \) are a function of \( E_1 \) and \( E_2 \) only, so comparisons can be made using stiffness ratios. The alternate forms are:

\[
\begin{align*}
\bar{Q}_{11} &= E_1 \cos^4 \theta + E_2 \\
\bar{Q}_{12} &= E_1 \sin^2 \theta \cos^2 \theta + E_2 / 2
\end{align*}
\] (19-20)
The question arises, when are Chou’s approximations for $\bar{Q}_{ij}$ suitable to use? Both the exact and approximate transformed stiffnesses, using Graphite/RP6410 polyurethane are plotted in Figure 2. Note there is no appreciable difference. For a typical graphite/epoxy laminate, there is a considerable difference.

Using the transformed stiffnesses $\bar{Q}_{ij}$, the stress-strain relationship becomes:

$$
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{bmatrix} = 
\begin{bmatrix}
\bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\
\bar{Q}_{21} & \bar{Q}_{22} & \bar{Q}_{26} \\
\bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{bmatrix}
$$

(25)

The extensional stiffness, coupling and bending stiffness matrices are denoted by $A_{ij}$, $B_{ij}$ and $D_{ij}$, respectively, and can be assembled by summing the contributions from each of n layers. For each lamina (e.g., $k^{th}$ layer) its mid-plane is a distance $z_k$ from the mid-plane of the total laminate:

$$
A_{ij} = \sum \bar{Q}_{ij} (z_k - z_{k-1}) ,
B_{ij} = \frac{1}{2} \sum \bar{Q}_{ij} (z_k^2 - z_{k-1}^2) ,
D_{ij} = \frac{1}{3} \sum \bar{Q}_{ij} (z_k^3 - z_{k-1}^3)
$$

(26)

Finally, stress and moment resultants can be obtained from mid-plane strains and curvatures using the matrix relation

$$
\bar{Q}_{22} = E_1 \sin^4 \theta + E_2
\bar{Q}_{16} = E_1 \sin \theta \cos^3 \theta
\bar{Q}_{26} = E_1 \sin^3 \theta \cos \theta
\bar{Q}_{66} = E_1 \sin^2 \theta \cos^2 \theta + E_2 / 4
$$

(21)-(24)
\[
\begin{bmatrix}
N_i \\
M_j
\end{bmatrix} =
\begin{bmatrix}
A_{ij} & B_{ij} \\
B_{ij} & D_{ij}
\end{bmatrix}
\begin{bmatrix}
\epsilon_i \\
k_j
\end{bmatrix}
\] (27)

Where \(N_i\) are inplane forces per unit width, \(M_j\) are bending moments per unit width, \(\epsilon_i\) are mid-plane strains, and \(k_j\) are mid-plane curvatures. Note that for symmetric laminates, the \(B_{ij}\) terms are zero, and additionally, if the symmetric laminate is balanced, (that is for every \(+\theta\) layer, there is a \(-\theta\) layer, such as seen in symmetric angle ply laminates, \([\theta/-\theta]\), then all 16 and 26 terms (in \(Q_{ij}, A_{ij}, B_{ij}\) and \(D_{ij}\)) will sum to zero as well for identical ply thicknesses. A more complete discussion is found in [17].

3.3 Prediction of Laminate Poisson’s Ratios  
Starting with equation 27, one may derive the laminate’s major PR. The laminate inplane PR is defined as

\[
\nu_{xy} = \frac{A_{12}A_{66} - A_{16}A_{26}}{A_{22}A_{66} - A_{26}^2}. 
\] (28)

If one assumes a laminate to be balanced, or consider an angle-ply construction, or that the \(A_{16}\) and \(A_{26}\) terms are negligible, and the more familiar form

\[
\nu_{xy} = \frac{A_{12}}{A_{22}} 
\] (29)

is produced. However, not considering the inplane shear-coupling effects of \(A_{16}\) and \(A_{26}\) can produce erroneous results. Laminate designers should stay away from the use of equation 29.

4.0 PRESENTATION AND DISCUSSION OF DATA

Poisson’s ratios as a function of angle for a graphite/epoxy angle-ply laminate (symmetric & balanced) are shown in Figure 3 using CLT and Chou’s approximations. It is evident that Chou’s approximation is good only for high ratios of \(E_1/E_2\). Note that even for a traditional composite, that PRs up to 1.5 are possible. Chou’s approximation will always predict \(\nu_{xy}\) to be 0.5 at a laminate orientation of 0°, which may be close for some elastomer composites.

4.1 High Poisson’s Ratios  
If one uses equations 19-24, and divides all terms by \(E_1\), it is possible to obtain PRs as a function of a stiffness ratio \(E_1/E_2\). Most fiberglass and graphite composites have a stiffness ratio of about 8 to 16, while a fiberglass or graphite reinforced RP 6410 polyurethane will have stiffness ratios between 5,000 and 50,000, depending on fiber volume fractions and fiber stiffness. Poisson’s ratios for a number of stiffness ratios and composites are given in Figure 4. They are considered symmetric, balanced angle-ply laminates. Equations 19-24, modified to use the stiffness ratio \(E_1/E_2\), were used for FRE and FRE-like combinations. The IM7/ 6410 material properties were obtained from a related study [13], and have a fiber volume fraction of 42%. Maximum PRs range from 40 to 100 at off-axis angles ranging from about 4 to 7 degrees. With some effort it should be possible to maximize \(\nu_{xy}\) with respect to \(\theta\) and determine the maximum PR with respect to \(\theta\) for a given stiffness ratio. For all FRE combinations, PRs converge to 3 at 30° and to 1 at 45°.
Figure 3  Poisson’s Ratio as a function of angle for a graphite/epoxy angle-ply laminate.

Figure 4  Poisson’s Ratio as a function of off-axis angle for various stiffness ratios and composites.
This is true for CLT or Chou’s approximations and is a function of the transformation equations used. Chou’s approximations will always predict a PR of 0.5 at 0° while CLT will give the actual value for an orthotropic laminate.

**4.2 Implications of High Poisson’s Ratios** If ratios of up to 100 are possible, what does this mean? Can they be measured, and will one obtain large transverse strains? Also, what applications will make use of high PRs? If one takes a strip of IM7/6410 FRE at [5/-5], 2.5 cm (1 in) wide, 5 mm (.2 in) thick and applies a tensile load of 4450 N (1000 lb), the resulting axial and transverse strains are only 0.0009 and 0.08, respectively. Hence, using FRE angle-ply laminates to obtain large transverse strains at low angles is not realistic. However, if one changes the layup to [15/-15], the same axial load will produce axial and transverse strains of 0.057 and −0.78 respectively. Note that laminate shear strains are zero, but ply shear strains are not. Therefore, one should tailor his laminate to produce the largest strains, if desired, rather than the largest ratio.

![Figure 5](image)

**Figure 5** Experimental test results and predicted Poisson’s ratio as a function of off-axis angle for various stiffness ratios and composites.

**4.3 Experimental Verification** Verifying these predictions has proven difficult, but some results are compared to predictions in Figure 5. Angle-ply laminates fabricated from fiberglass / Silastic S silicone, and fiberglass / RP6410 polyurethane, with off-axis angles ranging from 0° to 90°, were tested and documented in a previous work [15]. At 45° an average PR of 1.21 was obtained. Tests on the fiberglass / silicone produced a PR of 3.03 at 30°. In a predecessor (student) project, a student fabricated graphite/ RP6410 specimens, of undetermined fiber volume fraction, at off-axis angles of 5° and 15°. Ratios of 14.1 and 7.5 were obtained for the 5° and 15° specimens respectively. An indirect method, where axial and transverse strains as a
function of load were measured, slopes of linear portions of the curves were obtained, and a ratio taken, to obtain the final inplane major PR. *These experimental data points show that high Poisson’s ratios are possible, even though some are much less than predicted.*

With stiffer fibers i.e. fiberglass and graphite, it has been very difficult to grip and test specimens with low off-axis angles. It is thought that for these laminates, the thickness PR is also very high, and any axial load will immediately loosen the specimen in its grips and it will begin to slip. Offset roller grips were fabricated and tested but the friction between rollers and specimen was not always sufficient to engage the roller or load up the fibers. The next method will be to filament wind a continuous loop of elastomer-composite, over a dissolvable mandrel, and then load the loop between two parallel bars. New data acquisition equipment will increase the resolution or level of axial and transverse strain that can be recorded.

4.4 *Prediction of Negative Poisson’s Ratios* If a laminate has highly orthotropic constitutive materials, and contains an unbalanced lay-up, for example a \([\theta/\alpha]\), lay-up, it is possible to obtain a solid (non-foam) laminate with a negative PR or \(\nu_{xy}\). We can see in Figure 6, that negative PRs are possible for graphite/epoxy laminates, although the values are quite small. Note that for an inner ply angle, \(\alpha\), of 0 and 90, ratios for all values of \(\theta\) are positive. Note the bimodal nature of the ratios for \(\alpha\) between 20 and 70. Many fabrication methods, and design methodologies are conducive to balanced laminates because of reduced shear coupling effects. If one uses the same

![Figure 6](image-url)  
*Figure 6  Poisson’s ratio as a function of angle for a graphite / epoxy laminate with a lay-up of \([\theta/\alpha]\), where \(\theta\) varies and \(\alpha\) is constant.*
lay-up scheme as before, but uses a graphite / polyurethane material, such as the IM7/RP6410 listed, the PRs reach extremely negative values, as found in Figure 7. Notice again that the ratios are bimodal in nature when plotted as a function of the outer ply angle, $\theta$. The PRs are slightly positive at $0^\circ$, $\alpha$, and at $90^\circ$. The PRs for $\alpha = 45^\circ$ and above are similar to $\alpha = 30^\circ$, but decrease in magnitude after $45^\circ$.

![Graph showing Poisson's ratio as a function of angle](image)

Figure 7  Poisson’s ratio as a function of angle for a gr/polyurethane laminate with a lay-up of $[\theta/\alpha]$, where $\alpha$ is held fixed and $\theta$ is varied.

5.0 SIMPLE EXAMPLES OF APPLICATIONS

As noted in the literature review, auxetics or negative Poisson’s ratio materials are being considered for use in vibration damping. Other possible uses include solid-state actuators, crash helmets, body armor, biomimetics, and fasteners.

For example, if one can find a way to bond a polyurethane elastomer to Nitinol, a common shape memory alloy (SMA), it may be possible to create a solid-state actuator. The actuator could use either the extremely large positive or negative ratios developed above. In Figure 8 is plotted the PR for an angle-ply Nitinol/RP6410 composite where the off-axis angle and fiber volume fraction is varied. Note that the maximum PR only decreases by 10% for a 50% decrease in fiber volume fraction. If one took a strip of nitinol/RP6410, laminated at $[5/-5]_s$, 2.5 cm (1 in) wide and long, and .5 cm (.2 in) in total thickness, a 4% contraction in the length of the nitinol wire should theoretically produce an expansion in the $y$ or transverse direction of 220%. This would make the strip 5.5 cm (2.2 in) wide. However this would only result in a 3.6 N (.8 lb) outward
If the SMA laminate angle was changed to 15°, the strip would only expand to 3.88 cm (1.52 in), but the force generated would increase to 29.5 N (6.6 lb). In reality there is a volume change in SMA wires during actuation, so the actual amount of transverse expansion may be smaller. Nevertheless, such a device may be especially useful for MEMS and nano-size applications, where large displacements are needed, large forces are not and solid-state construction is desired. Nano-machines may be a highly profitable area because of the ability of chip foundries to place regions and layers of alternating stiff and compliant materials next to each other. Changes in Nitinol fiber volume fraction would affect the force output, but would not affect transverse displacements significantly.

![Graph showing Poisson's ratio as a function of off-axis angle for Nitinol/RP6410 over a range of fiber volume fractions.](image)

Vibration damping appears to be a driver for the use of auxetic or negative Poisson’s ratio materials. In a related study [13], highly orthotropic elastomer composite laminates were bonded to aluminum plates. Two panels had balanced lay-ups, [+15/-15/+30/-30/aluminum/-15/+15/-30/+30] that produced high PRs in the skins. Two other panels used unbalanced lay-ups, [15/30/aluminum/30/15] that produced negative Poisson’s ratios in the skins. Both sets of panels produced high loss factors, but the negative PR skin loss factors were considerably higher than their counterparts. Although the fiber-reinforced elastomers (FRE) produce high damping, they may not be suitable for all applications because of their low transverse stiffness.

One solution is to assemble a hybrid graphite/epoxy and graphite/elastomer laminate. Damping could be increased over a traditional laminate, and transverse stiffness could be maintained. In Figure 9, PRs are plotted for a hybrid IM7/8551-7a and IM7/RP6410 laminate with a lay-up of
The graphite/epoxy are in the outer plies, and constitute half of the total laminate thickness. Note that the maximum negative PRs are only twice that of a laminate made only of graphite/epoxy. The negative values could be increased through optimization, one avenue is to increase the thickness of the FRE plies. An increase of the FRE plies to 70% of total thickness yields a maximum negative PR of approximately −1.5. The alternating FRE/composite layers will also increase damping through the constrained layer effect.

Another method would be to use a rigid elastomer, such as Huntsman’s RP 6444. It’s initial Young’s modulus is approximately 30,000 psi. A negative Poisson’s ratio laminate fabricated from IM7/RP 6444 will yield a maximum PR of approximately −10.

![Figure 9](image-url)  

**Figure 9** Poisson’s ratio as a function of off-axis angle for a symmetric hybrid laminate of Gr/Ep over a range of angles θ, and Gr/RP6410 over α.

### 6.0 SUMMARY

In an exploratory work, the background, theory, and materials have been developed to show that very large Poisson’s ratios, perhaps over 100, are possible for solid (non-foam) fiber-reinforced elastomer laminates. It has also been shown that by using certain lay-up schedules, that negative Poisson’s ratios much greater than those produced by foam and foam-like structures, perhaps as great as −60, can be produced. Difficulties in the gripping of FRE specimens have limited the number of experimental results, but a new configuration is being developed. If unbalanced FRE laminates can be used in structures where traditional composites are used currently, significant increases in vibration damping, and tailorable of elastic response could be achieved. In examples of simple applications, it is seen that high Poisson’s ratio SMA laminates might be used as solid-state actuators, with strong potential for micro- and nano-structures. Results from a
comparison of high and negative Poisson’s ratio FRE laminates used in damping indicate that both give excellent results, but that the negative Poisson’s ratio laminates are best. It may be possible to develop hybrid FRE/traditional composites to exploit the advantages of both.

7.0 REFERENCES