A GRAPHICAL APPROACH FOR ASSESSING HIGH-STRENGTH FIBER PERFORMANCE

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ABSTRACT

The design and materials *used for bullet-resistant body armor have evolved continuously to keep up with the threats. In this paper, a graphical approach is presented that plots the potential strain energy absorption of some common high-performance fibers relative to their sound velocities. These data emphasize the results of Roylance and Wang and Phoenix and Porwal that optimal ballistic performance in soft body armor applications arises from a balance between the specific strain energy absorption and sound velocity of the fiber. By comparing data in the literature on fibers used in ballistic applications, inferences can be made about how energy absorption and sound velocity may influence ballistic resistance. In addition, these types of comparison plots may provide critical insight as to how molecular structure can impact short and long-term ballistic performance.

1. INTRODUCTION

It is generally accepted that the modulus, ultimate tensile strength, and strain-to-failure of the fibers used in ballistic applications are important properties to consider when assessing soft body armor (SBA) performance.[1,2] Therefore, it is not surprising that a considerable amount of research has focused on determining the susceptibility of these fibers to chemical and mechanical degradation. Recent research[3-6] have demonstrated the impact of these degradation pathways on the mechanical properties of poly (*p*-phenylene benzobisoxazole) (PBO) and poly (*p*-phenylene terephthalamide) (PPT) fibers.

With the continued development of new high-impact fibers, a long-term goal of the National Institute of Standards and Technology (NIST) high-strength fiber research program is the development of a framework for evaluating improvements in the next generation of fibers that may be used in SBA, while anticipating their long-term performance. This has proven to be a challenging task given the wide variety of fibers that have been considered for SBA applications, the various types of ballistic threats that must be thwarted, and recent research efforts to incorporate nanotechnology into ballistic applications.

Recent empirical[7,8] and theoretical developments,[1,2] although insightful as to how the fiber properties may influence SBA performance, are generally limited to specific ballistic threats, such as right circular cylinder (RCC) projectiles. This paper seeks to use the existing body of literature on the basic material properties, molecular structure, and morphology of existing fibers used in ballistic applications to gain insight about how future fiber developments may enhance ballistic performance.

2. INSIGHTS FROM PRIOR RESEARCH

Of critical interest in SBA research is how can one accurately quantify the energy absorption mechanisms in soft body armor composed of woven fabrics (see Figure 1) and how these results are related to fiber properties? A limited review[1] of the transverse ballistic impact of woven fabrics indicates that numerical simulations and closed formed membrane solutions are often used. In the following sub-sections, the research of Roylance and Wang[9] (numerical solution) and that of Phoenix and Porwal[1] (membrane solution) are cited as examples of each research approach.

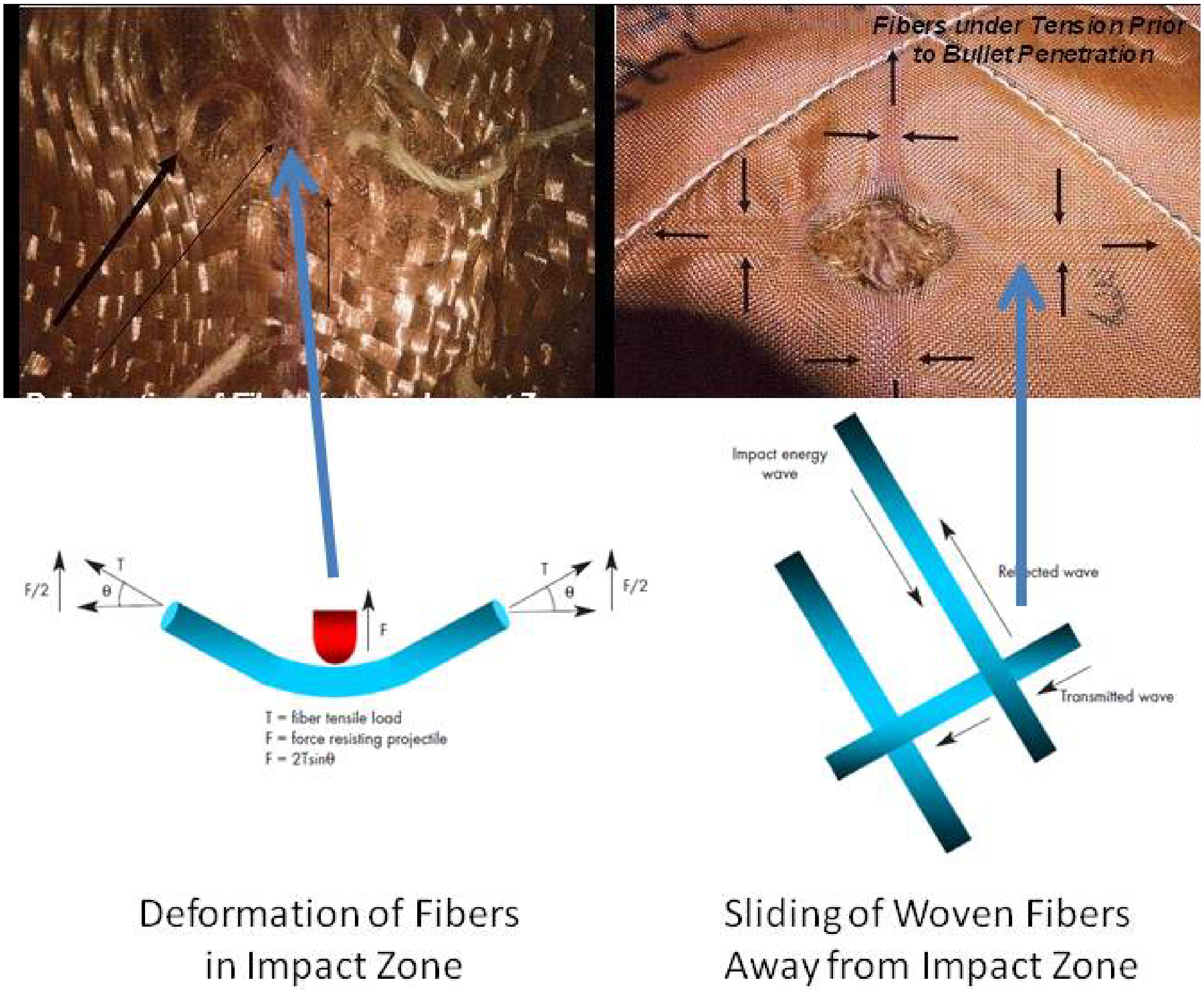

Figure 1. Accepted energy absorption mechanisms in soft body armor composed of woven fabrics *(adapted from reference 10)*.

Research[1] based on the membrane approach has identified several shortcomings associated with the numerical simulation approach of transverse impacts. These include (a) numerical 'ringing' oscillations, (b) a lack of attention paid to the projectile geometry and the size scale of the contact zone, and (c) the escalation of computational demands as system size is increased and microstructural features are incorporated. The numerical simulations can avoid certain limitations of the closed form membrane approach, which generally do not include secondary ballistic effects such as energy dissipation that arises from stress-wave interactions and reflections that occur at the fiber junction points (see Figure 1). Notwithstanding these limitations, the cited membrane solution and numerical simulation discussed below seem to advance, in some respects, consistent views of the ballistic impact process.

2.1 Roylance and Wang Numerical Simulation[9]

The research of Roylance and Wang underscores the concept that ballistic resistance is a balance between high-modulus fibers producing faster wave speeds and lower strains, and the fiber strain-to-failure. In their simulations of nylon, the PPT fibers denoted as Kevlar 29[†] and Kevlar 49, and graphite, the rate of energy absorption was found to increase monotonically with the fiber modulus. However, the high-modulus graphite fibers exhibit poor impact resistance due to its low breaking strain (see Figure 5 in reference 9).

When the original PPT fiber-based SBA was developed in the 1970s, blunt force trauma was considered a key factor in assessing ballistic performance. Roylance and Wang observed through their simulations that the level of strain at the impact point and the rate of propagation of the stress wave (energy) away from the impact location are governed by the fiber modulus and density. Thus graphite fibers, having the highest modulus of the four materials investigated, propagate the lowest level of strain at the highest rate. As the modulus decreases, the strain level at the impact point increases and the wave speed and rate of energy dissipated away from the impact zone decreases (see Figure 2 in reference 9).

2.2 Phoenix and Porwal Membrane Solution[1]

The theoretical development of Phoenix and Porwal has reaffirmed, for the case of a ballistic membrane impacted by a flat right circular cylinder (RCC) projectile, that the Cunniff equation[7,8] (see Equation 1) is potentially useful as a first-level screening tool for assessing the relative ballistic performance of fibers from their yarn (fiber) properties. For armor impacted by a flat RCC projectile, the factor $\left[\Omega\left\{m^3/s^3\right\}\right]^{1/3}$ (see see Equation 1) is a normalizing velocity that allows the relative comparison of fibers independent of the vest construction parameter known as the areal density ratio, Γ_0.

[†] "Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose."

$$\left[\Omega\left\{m^3/s^3\right\}\right]^{1/3} = \left[\frac{\sigma_y^{\max}\varepsilon_y^{\max}}{2\rho}\sqrt{\frac{E_y}{\rho}}\right]^{1/3} \qquad [1]$$

where

m	denotes meters
s	denotes seconds
$\sigma_y^{\max}$	is the yarn (fiber) maximum axial tensile strength
$\varepsilon_y^{\max}$	is the yarn (fiber) maximum tensile strain
ρ	is the yarn (fiber) density
E_y	is the yarn (fiber) longitudinal linear elastic modulus

From this equation, one observes that Ω is the product of the elastic energy storage capability of the fiber per unit mass ($\left[\left(\sigma_y^{\max}\varepsilon_y^{\max}\right)/(2\rho)\right]$, a measure of toughness) times the fiber's tensile wave speed, $a_{0y} = \sqrt{E_y/\rho}$. As described by Phoenix, increasing the elastic energy storage (often believed desirable for improved impact resistance) is not beneficial if a_{0y} is greatly reduced in the process. Another consequence of greatly lowering a_{0y} is the need for a much larger distance to stop the projectile, thereby greatly increasing the bulk of the body armor or allowing larger undesirable armor deformations that increase the risk of blunt force trauma.

3. ELASTIC STORED ENERGY VERSUS SOUND VELOCITY

From the above discussion, it seems plausible to compare the sound velocity of a fiber to its elastic stored energy, since the latter term incorporates the fiber strain-to-failure espoused by Roylance and Wang. Using data from multiple sources,[7,8,10-13] such a plot is shown in Figure 2 for a select group of high-performance fibers that span a wide range of sound velocities: (a) S-glass, (b) PPT, (c) carbon fiber, (d) polyester, (e) nylon, and (f) silk. Although the choice of fibers is somewhat arbitrary, these fibers have been considered for, are being used in, or are of historical interest for ballistic applications. Excluding the nylon data points, a power law trend line has been fit through these data ($R^2 = 0.97$) to aid the eye of the reader.

These data capture the general observation by Phoenix that increasing the elastic energy storage does no good if a_{0y} is greatly reduced in the process. For the plotted data, the graph underscores the observations by Roylance that the PPT fiber embodied in Kevlar 29, which has been widely used in soft body armor, achieves a balance between wave speed and energy absorption (compare Figures 2 and 5 from reference 9).

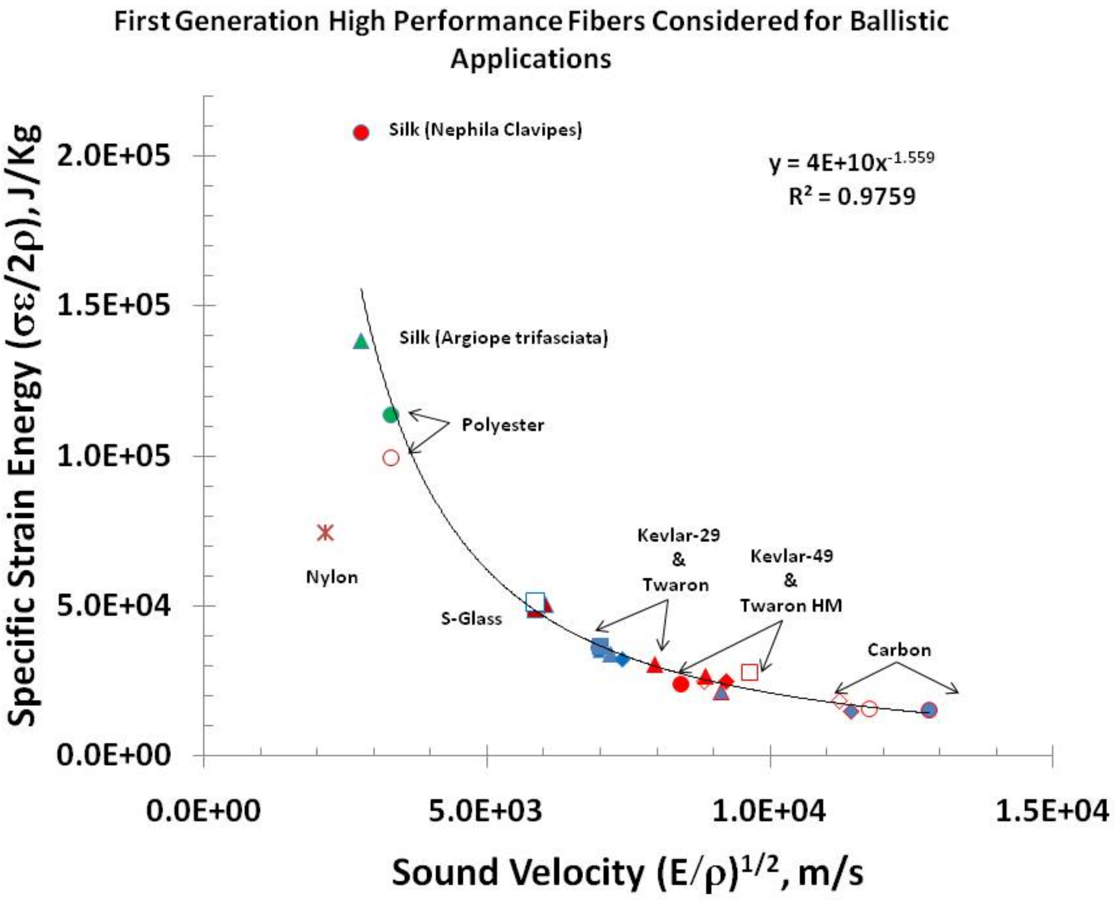

Figure 2. Plot of specific strain energy versus sound velocity for selected high-performance fibers.

The following examples illustrate how changes in processing and molecular structure can influence ballistic performance relative to the data presented in Figure 2**.** The second example also illustrates graphically, relative to the data presented in Figure 2, how changes in material properties caused by various degradation mechanisms can impact ballistic performance.

3.1 Example 1

Figure 3 illustrates how the plot in Figure 2 can be used to qualitatively evaluate the impact of fiber processing changes on ballistic performance. In Figure 3, the PPT fibers denoted as Kevlar KM2 and Kevlar 129 reportedly give improve ballistic fragmentation resistance and increased protection capabilities against conventional firearm threats such as the 9 mm Full Metal Jacket (FMJ) ammunition, respectively.[7,8,10,13,14] Although the vest design is clearly ignored in these analyses, the data indicates that increased energy absorption in the case of the Kevlar KM2 fibers relative to Kevlar 29 may be essential to achieve improved ballistic resistance against fragments, while increased sound velocity and a slight increase in specific strain energy absorption relative to Kevlar 29 fibers may be required to achieve increased protection against firearm threats.

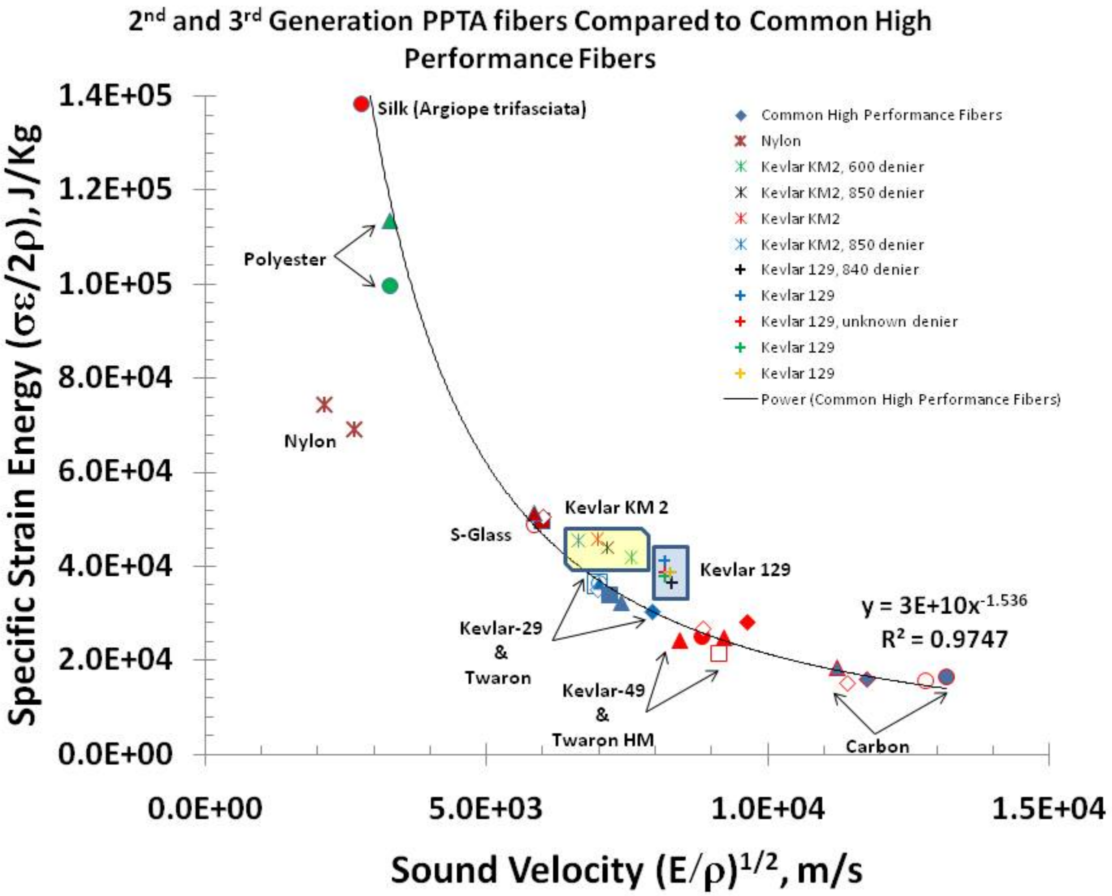

Figure 3. Comparison of the specific strain energy and sound velocity values of Kevlar KM2 and Kevlar 129 relative to the common high-performance fibers discussed in Figure 2.

3.2 Example 2

In Figure **4**, the properties of pristine PBO fibers are plotted to provide an example of how material property degradation influences the potential energy absorption of the fibers.[7,8,10,14] The sound velocities of PBO fibers are shown to be comparable to carbon fibers, which have a sound velocity greater than PPT fibers. Furthermore, the initial strain energy absorption of PBO fibers is comparable to that of S-glass fibers, which have a specific strain energy absorption greater than PPT fibers. Therefore, PBO fibers have the potential of absorbing more energy than PPT fibers while dissipating that energy over a wider range than PPT fibers. However, the reduction in strain-to-failure of the PBO fibers with degradation leads to a reduced specific strain energy comparable to that of carbon fibers, which were shown to be inferior to PPT fibers in ballistic performance because of their low strain to failure.

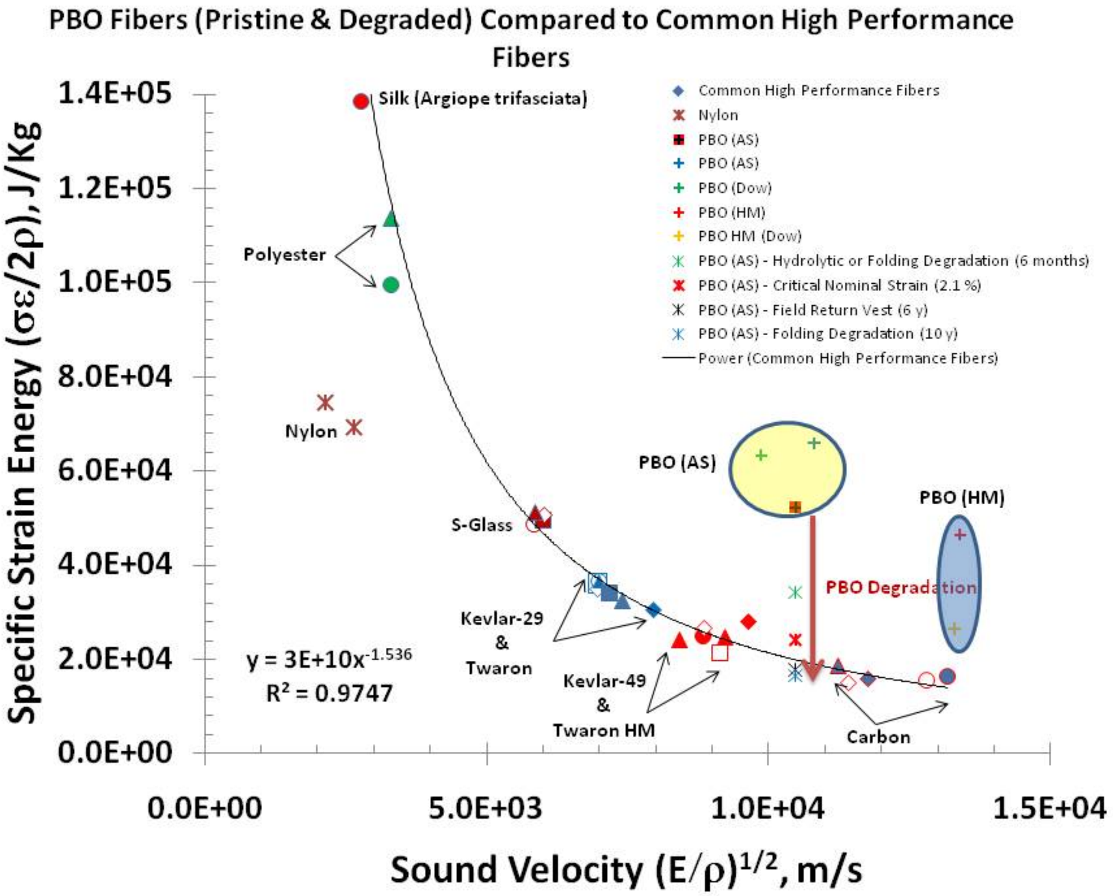

Figure 4. Specific strain energy versus sound velocity plot of pristine and degraded PBO fibers compared to common high-performance fibers.

4. CONCLUSIONS

A graphical approach is presented that plots the potential strain energy absorption of some common high-performance fibers relative to their sound velocities. These data underscore the results of Roylance and Wang and Phoenix and Porwal that optimal ballistic performance in SBA applications arises from a balance between the specific strain energy absorption and sound velocity of the fiber. By comparing more recently developed fibers to this set of fibers, inferences can be made about how energy absorption and sound velocity may influence ballistic resistance for fragments and small arms bullets. In addition, these types of comparison plots may provide critical insight about how molecular structure can impact short and long-term ballistic performance.

5. REFERENCES

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