Composite Materials for Ballistic Protective Helmets

Philip M. Cunniff

U.S. Army Soldier and Biological Chemical Command
Natick Soldier Center
Natick, MA 01760-5019

SUMMARY

The ballistic impact performance of several high performance fibers is investigated for application as ballistic protective helmet materials. Materials considered include Zylon® fiber with Kraton®, vinylester and thermoplastic polyester resins, a hybrid system comprised of carbon fiber with an epoxy resin (as the strikeface material) and Zylon® with a thermoplastic polyester resin (as the backface material), Spectra® 2000 fiber with a vinylester resin, and Spectra® 2000 consolidated without resin. Comparison of the performance of each material system is made to both the performance of 850 denier Kevlar® KM2 fiber with a polyvinylbutyral/phenolic resin and to the expected performance of optimized Zylon® armor systems.

KEYWORDS: Helmet, body armor, fragmentation protection, Zylon®, Spectra® 2000, Kevlar®

INTRODUCTION

The primary components of modern military helmets consist of a composite shell and a suspension system. However, these helmets may include global positioning system (GPS) and communications antennas, combat identification systems, vision enhancement systems, and heads-up computer displays. The addition of these added systems increases the total helmet weight and consequently increases fatigue due to this additional head-borne weight. A reduced weight helmet that provides the same or enhance ballistic impact protection compared to existing helmets has always been an important objective. The importance of reducing the overall helmet weight is increased with the incorporation of these additional systems to the modern military helmet.

Among other requirements, the ballistic protective materials shell and suspension system used in military helmets have structural rigidity and elasticity requirements, low velocity impact protection requirements, durability requirements, requirements for chemical and biological decontamination, requirements for environmental stability, requirements to mitigate the potential of blunt trauma injury [1, 2] and ballistic impact performance requirements. The ballistic impact requirements of the helmet may be specified after exposure to certain environmental conditions (e.g. temperature extremes, salt water, fresh water, POL, etc.), and may be required to maintain prescribed ballistic impact performance at off-normal impact obliquity. This paper focuses on the ballistic impact performance of a number of armor materials at 0-degree (normal) impact obliquity, and without pre-exposure to environmental insults, and consequently must be considered a preliminary evaluation of the performance of these systems.

The candidate armor materials investigated in this work are considered for potential replacement materials for the Personnel Armor System for Ground Troops (PASGT) helmet. The PASGT helmet is a composite prepared from 1500 denier 2X2 basket weave nominally 35X35 ends/picks per inch 14 oz/yd^2 Kevlar® 29 fabric coated with a 50/50 phenolic/polyvinylbutyral resin; the total areal density of the ballistic protective materials used in the helmet is 11.6 kg/m^2 (2.4 lb/ft^2). Due to the curvature of the helmet, continuous-ply sheet goods are seldom used to construct these helmets, since it is difficult to maintain constant areal density within the helmet shell with this construction technique. Typical military helmets are effectively made up of a patchwork of discontinuous fabric plies. For the purpose of this report, the impact performance of candidate materials was evaluated using results obtained from continuous ply flat panel.

In the case of Kevlar® 29 polyvinyl butyral / phenolic composite armor systems, the ballistic impact performance of helmets made from these materials is found to be well approximated from the impact performance of flat panels constructed from similar continuous-ply materials, as indicated in Figure 1. In Figure 1, the V50 ballistic impact performance of the Kevlar® 29 helmets and flat panels is plotted along with a best-fit to Equation 1. The helmet data of Figure 1 represents data collected from helmets at 5.5, 6.1, 9.2 and 11.6 kg/m^2 areal density impacted by 2, 4, 16, and 64 grain steel right circular cylindrical projectiles.

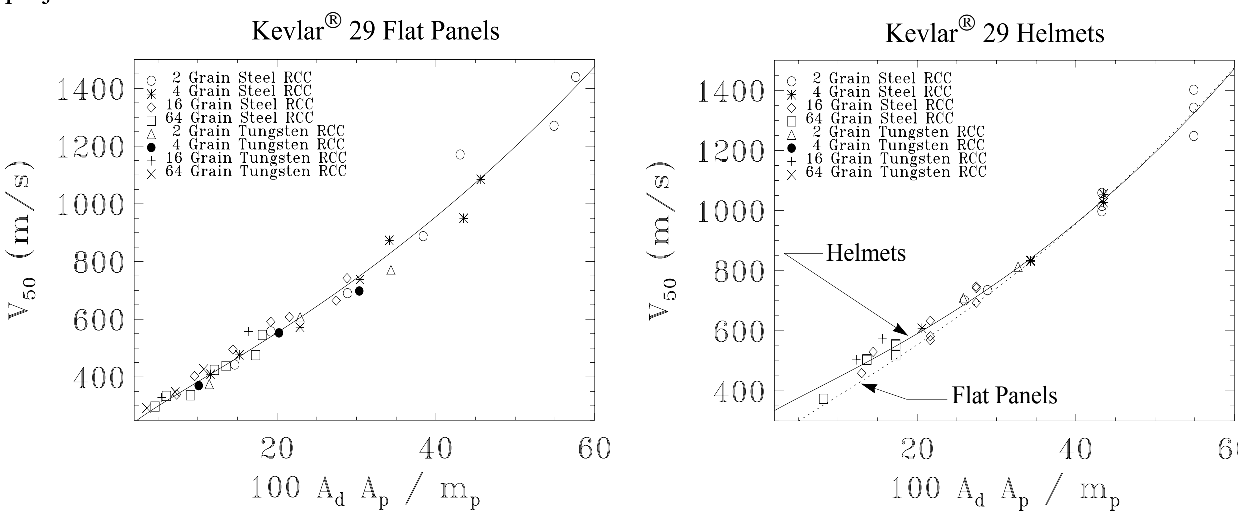

Fig. 1. V50 Performance of 1500 denier 2X2 Basket Weave Kevlar® 29 Polyvinylbutyral-Phenolic Composites and Helmets

The flat panel data of Figure 1 represents data collected from flat panels at 3.1, 4.1, 6.1 8.1, 9.1, 11.6 and 12.2 kg/m^2 areal density impacted by 2, 4, 16, and 64 grain steel and tungsten right circular cylindrical projectiles. As illustrated in Figure 1, for V50 velocities above about 600 m/s, the performance of helmets is well approximated by the flat panel data. The flat panel data is conservative for low for ballistic limits below about 600 m/s. Best fit regression coefficients for the data of Figure 1, using equation 1 are presented in Table 1

$$V_{50} = X_5 e^{X_6 (A_d A_p / m_p)^{X_7}} \quad (1)$$

Table 1: Regression Constants for Kevlar® 29 PVB Phenolic Materials

Regression Coefficient	Flat Panel Value	Helmet System Value
X_5	173.192	298.274
X_6	2.81987	2.36866
X_7	0.56921	0.772738

The use of flat panel data to approximate the performance of helmets is further reinforced by examination of the V50 performance of Kevlar® KM2 armor materials. Figure 2 illustrates data collected from two helmet systems at an areal density of 10.2 kg/m^2 impacted by 2, 4, 16, and 64 grain steel right circular cylindrical projectiles, and flat panel data collected from continuous-ply flat panels at 3.9, 7.9 and 12.1 kg/m^2 areal density impacted by 2, 4, 16, and 64 grain steel and tungsten right circular cylindrical projectiles. It is noteworthy that the 64-grain data point at about $100A_dA_p/m_p$ of about 15 that lies below the smooth curve of Figure 2 was obtained from a helmet system.

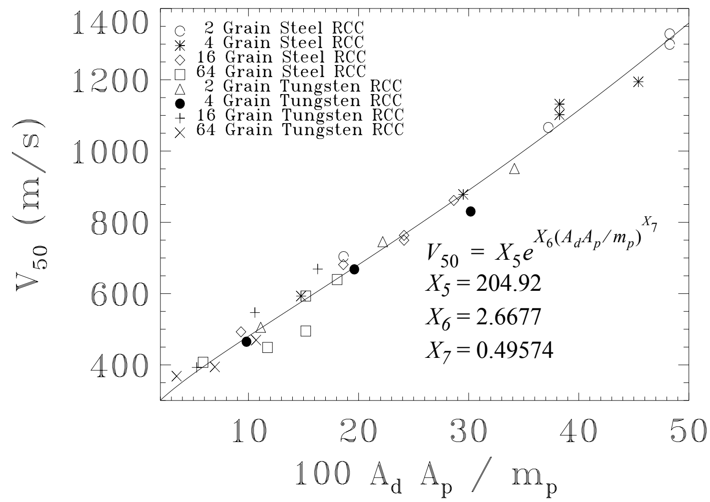

Fig. 2. V50 Performance of 850 denier plain weave Kevlar® KM2 polyvinylbutyral-phenolic composites and helmets.

ARMOR SYSTEM PERFORMANCE GOALS

A goal helmet areal density of 8.5 kg/m^2 (1.75 lb/ft^2) (for the ballistic protective materials) was used as an objective for this work; the goal performance for flat panels was selected to be equal performance to Kevlar® 29 PVB/ phenolic helmets at 2/3 the weight of the Kevlar® systems. A comparison of this goal to the impact performance of Kevlar® 29 and Kevlar® KM2 PVB/phenolic armor systems is provided in Figure 3. To aid in the evaluation of candidate armor system performance, a set of dimensionless parameters for the optimization of textile-based body armor systems, previously described by Cunniff [3], was adapted to rank the performance of the armor systems. The dimensionless parameters allow an armor developer to determine the extent to which armor system construction parameters have enhanced (or degraded) the potential of an existing fiber to perform as an armor material.

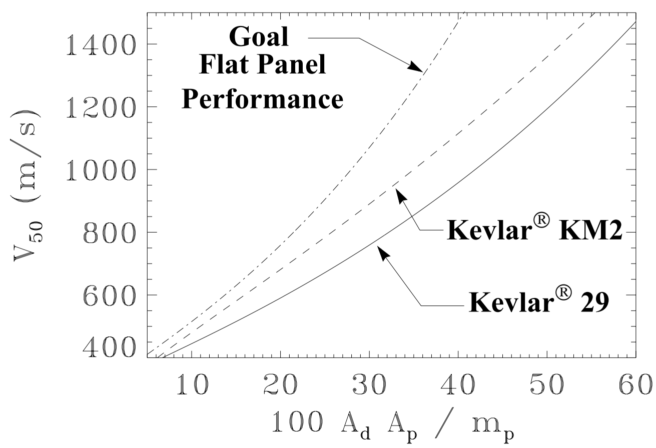

Fig. 3. Helmet performance goals

A number of construction parameters are known to affect armor system performance. For example, the extent to which damage is introduced into the fibers during production is expected to directly correlate with impact performance. Damage to the fibers of an armor system may be introduced during weaving, scouring, and prepregging; additional damage to the fibers may occur due to environmental degradation. Additionally, the performance of composite armor may be affected by resin content, resin to fiber adhesion and resin wet-out. Other construction parameters, such as ply areal density, fiber denier, and yarn denier, yarn finish, yarn twist, and warp and fill yarn crimp may also affect armor system performance. The result of the dimensional analysis may be used to set a goal for the performance of an armor material that reflects the potential of the fiber used in the armor system to perform as an armor material. For the purpose of this work, the dimensionless parameters are used to approximate the goal performance characteristics of optimized Zylon® armor. Comparison of each armor material system to the expected performance of optimized Zylon® armor and to the observed performance of Kevlar® KM2 armor is made throughout the paper. Kevlar® KM2 armor systems were found to perform marginally better than the predictions of the dimensional analysis [3]. This was attributed to enhanced construction of these systems compared to other armor systems considered in the dimensional analysis, and to a novel adhesion modifier used in the Kevlar® KM2 armor systems. The expected performance of optimized Zylon® armor was set using Kevlar® KM2 as the baseline; we assume the goal performance of Zylon® to use construction parameters at least as good as the Kevlar® KM2 armor.

The result of the dimensional analysis yields a dimensionless V50 velocity, which is defined as the V50 velocity normalized by the cube root of the product of specific work to break the fiber and the acoustic wave speed in the fiber, as indicated in Equation 2.

$$\Phi\left(\frac{V_{50}}{(U^*)^{1/3}} \quad , \quad \frac{A_d A_p}{m_p}\right) = 0 \qquad (2)$$

σ	- Fiber ultimate axial tensile strength		A_p	- Projectile presented area
ε	- Fiber ultimate tensile strain		m_p	- Projectile mass
ρ	- Fiber density		V_{50}	- V50 ballistic limit
E	- Fiber modulus (assumed linearly elastic)		A_d	- System areal density

U^* - the product of fiber specific toughness and strain wave velocity $U^* = \frac{\sigma\varepsilon}{2\rho}\sqrt{\frac{E}{\rho}}$

Tabulated values of $(U^*)^{1/3}$ for the armor materials considered for the present work are provided in Table 2. The expected performance of optimized Zylon® armor was set by scaling the observed V50 performance of Kevlar® KM2 PVB/phenolic armor by the ratio of the $(U^*)^{1/3}$ numbers for Zylon® and Kevlar® KM2.

Table 2: Fiber Mechanical Properties

Fiber	Strength (σ) (GPa)	Failure Strain (ε) (%)	Density (ρ) (kg/m^3)	Modulus (E) (GPa)	$(U)^{\frac{1}{3}}$ (m/s)
PBO	5.20	3.10	1560	169	813
185 denier Spectra® 2000	3.25	2.9	970	116	809
850 denier Kevlar® KM2	3.34	3.80	1440	73.7	681

CANDIDATE ARMOR SYSTEMS

Construction details of candidate armor systems prepared for this work are tabulated in Table 3. Extracted warp and fill yarn mechanical properties were obtained for most of the candidate armor materials. The quasi-static stress-strain response of yarns extracted from the fabrics was determined using a nominal 10-inch gauge length yarn tested in an Instron tensile tester.

Table 3: Construction Parameters/Mechanical Properties of Candidate Armor Materials

Target Type	Denier	Ply Areal Density (oz/yd^2)	Thread Count (in^{-1})	Yarn Strength (warp/fill) (gpd)	Yarn Crimp (warp/fill) (%)	Weave Type
Zylon® uni Polyester Composite	500	6.9	NA	NM	0/0	unidirectional
Zylon® Vinylester Composite	500	4.72	32X31	31.2 / 34.3	1.3/1.3	Plain
Zylon® Vinylester Composite	500	5.31	35X35	24.0 / 31.7	3.1/3.1	Plain
Zylon®Kraton® Composite	500	3.31	24X23	23.8 / 26.6	1.7/3.1	Plain
Zylon® Kraton® Composite	500	4.65	32X31	24.1 / 25.5	4.4/0.63	Plain
Zylon® Kraton® Composite	500	5.25	35X35	25.7/26.4	4.4/2.5	Plain
Zylon® Kraton® Composite	500	6.47	41X41	21.7 / 25.7	8.8/1.25	Plain
Zylon® Kraton® Composite	500	7.30	48X48	27.2 / 28.6	3.8/6.9	2X2 Basket
Spectra® 2000 Composite (no resin)	185	2.3	49X49			Plain
Spectra® 2000 Vinylester Composite	185	3.3	55X55	39.5 / 40.6	3.8/3.2	Plain
Spectra® 2000 Vinylester Composite	185	3.55	60X60	35.8 / 36.4	3.8/1.3	Plain

SPECTRA® 2000 FABRIC-BASED COMPOSITES

Several 185 denier Spectra® 2000 fabrics (coated to a weight of 3.3 oz/yd^2 for a 55X55 fabric, and 3.55 oz/yd^2 for a 60X60 fabric) were coated to a nominal 12% resin content with a vinylester resin. These were consolidated in a compression molding machine. Processing conditions included a temperature ramp to 120°C at a consolidation pressure of 60 bar (900 psi), a 30 minute soak at 120°C and 900 psi, and a cooling cycle from 120 to 50°C at 900 psi. Additionally, a 49X49 end/pick per inch fabric system was compression molded (without a resin system) at 140°C for 30 minutes at 140 bar (2000 psi) and cooled under pressure to approximately 50 °C.

V50 ballistic impact tests were conducted on the Spectra® 2000/vinylester composites using 2-, 4-, 16- and 64-grain steel right circular cylindrical steel projectiles on nominal 1.0 and 1.5 lb/ft^2 flat panels; V50 ballistic impact tests were conducted on the Spectra® 2000 composites consolidated without a resin using 4-, and 64-grain steel right circular cylindrical steel projectiles on nominal 1.0 lb/ft^2 flat panel composites. Results of the V50 tests are illustrated in Figure 4.

V50 results for Spectra® vinylester composites are seen to be slightly inferior to the expected performance for Zylon® composites. Results of the limited testing conducted on 49X49 Spectra® 2000 fabrics consolidated without a resin appear promising.

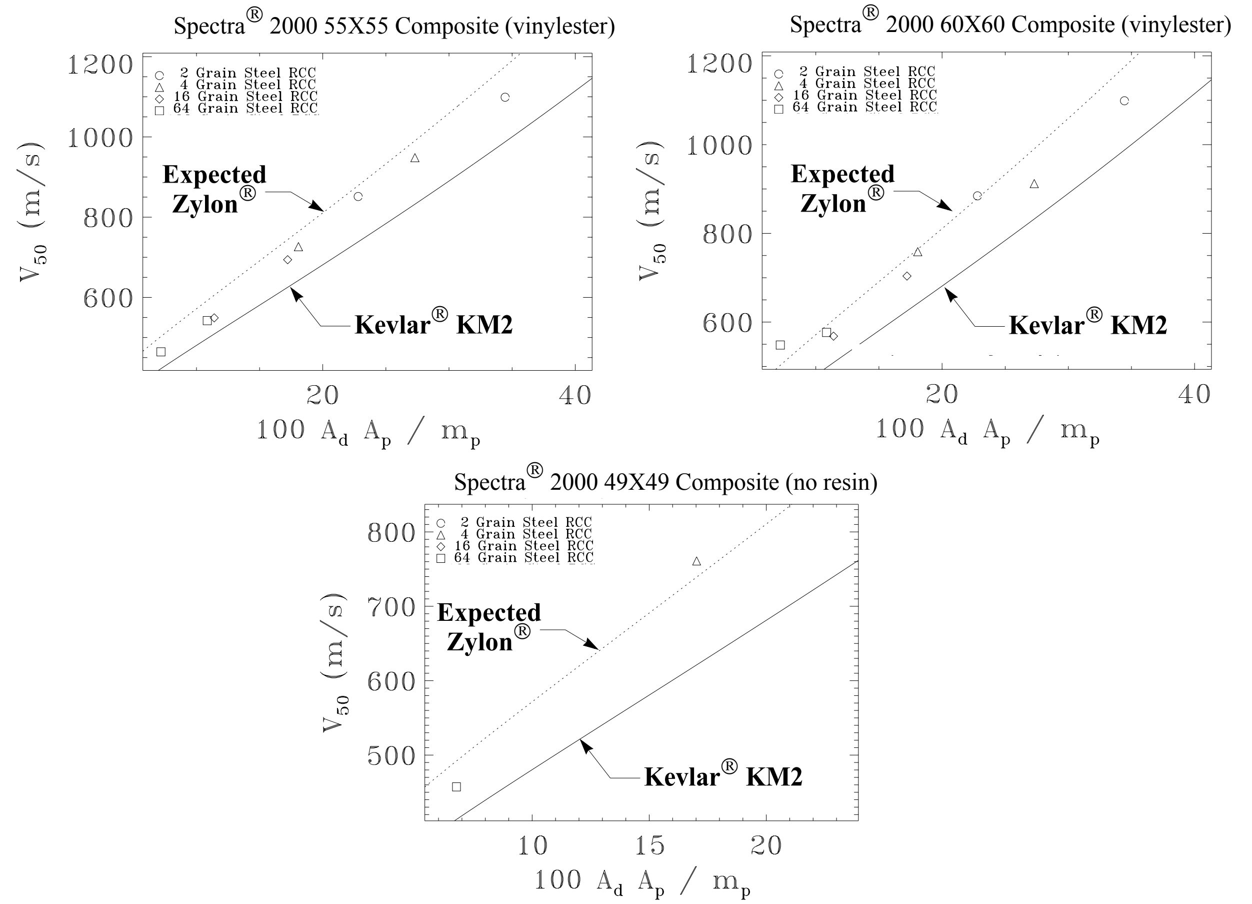

Fig. 4. V50 performance of 55X55 and 60X60 Spectra® 2000 fabrics with a vinylester resin; V50 performance of 49X49 Spectra® 2000 fabrics consolidated with no resin

ZYLON® FABRIC-BASED COMPOSITES

Several 500 denier Zylon® water repellent treated fabrics (coated to a weight of 3.31 oz/yd^2 for a 24X23 fabric, 4.65 oz/yd^2 for a 32X31 fabric, 5.25 oz/yd^2 for a 35X35 fabric, 6.47 oz/yd^2 for a 41X41 fabric, and 7.30 oz/yd^2 for a 48X48 fabric) were coated to a nominal 12% resin content with a Kraton® resin. V50 ballistic impact tests were conducted using 2-, and 16-grain steel right circular cylindrical steel projectiles and a 1-grain steel sphere on the unconsolidated fabrics using nominal 0.5 and 1.0 lb/ft^2 flat panels. Results of the V50 tests are illustrated in Figure 5.

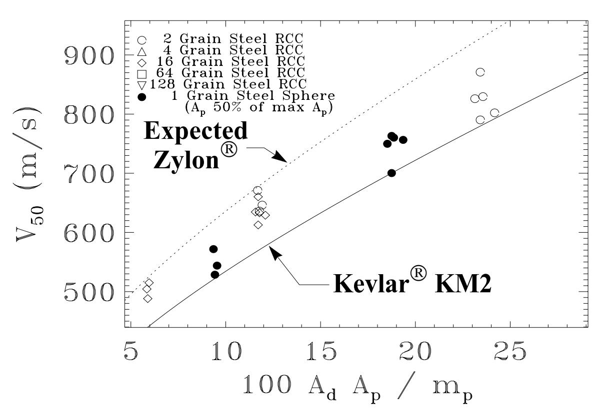

Fig. 5. V50 performance of Kraton-coated 500 denier Zylon® fabrics

In Figure 5, V50 results for Kraton® coated Zylon® fabrics are seen to be widely scattered, and consistently inferior to the expected performance for Zylon® fabrics; this is consistent with expectations, since the additional weight of the resin was expected to detract from performance of the armor systems (particularly against larger calibre cylinders). Additionally, each of the Zylon® fabrics was severely damaged during production of the fabrics, as indicated in Table 3.

These Kraton® coated Zylon® materials were also consolidated in a compression molding machine. Processing conditions included a temperature ramp to 120°C at a consolidation pressure of 60 bar (900 psi), a 30 minute soak at 120°C and 900 psi, and a cooling cycle from 120 to 50°C at 900 psi. V50 ballistic impact tests were conducted using 2-, and 16-grain steel right circular cylindrical steel projectiles using nominal 1.0 and 1.5 lb/ft^2 flat panels. Results of the V50 tests are illustrated in Figure 6. Composites prepared from these Kraton® coated fabrics yielded similarly widely scattered results, and also consistently under-performed expected Zylon® performance; presumably a result of the low extracted yarn strength.

Several 500 denier Zylon® water repellent treated fabrics (coated to a weight of 4.72 oz/yd^2 for a 32X31 fabric, and 5.31oz/yd^2 for a 35X35 fabric) were coated with a nominal 12% resin content vinylester resin. These were consolidated in a compression molding machine. Processing conditions included a temperature ramp to 120 °C at a consolidation pressure of 60 bar (900 psi), a 30 minute soak at 120°C and 900 psi, and a cooling cycle from 120 to 50°C at 900 psi. V50 ballistic impact tests were conducted using 2- and 16-grain steel right circular cylindrical steel projectiles using nominal 1.0 and 1.5 lb/ft^2 flat panels. Results of the V50 tests are illustrated in Figure 6.

Composites prepared from vinylester coated fabrics yielded much less scattered results, but also consistently under performed expected Zylon® performance, presumably for the same reason that the Zylon®/Kraton® composites failed to preform up to expectations. The small difference in performance of these two armor systems was unexpected, since one of the fabrics (the 5.31 oz/yd^2 35X35 fabric) was much more severely damaged in the warp direction than the other fabric.

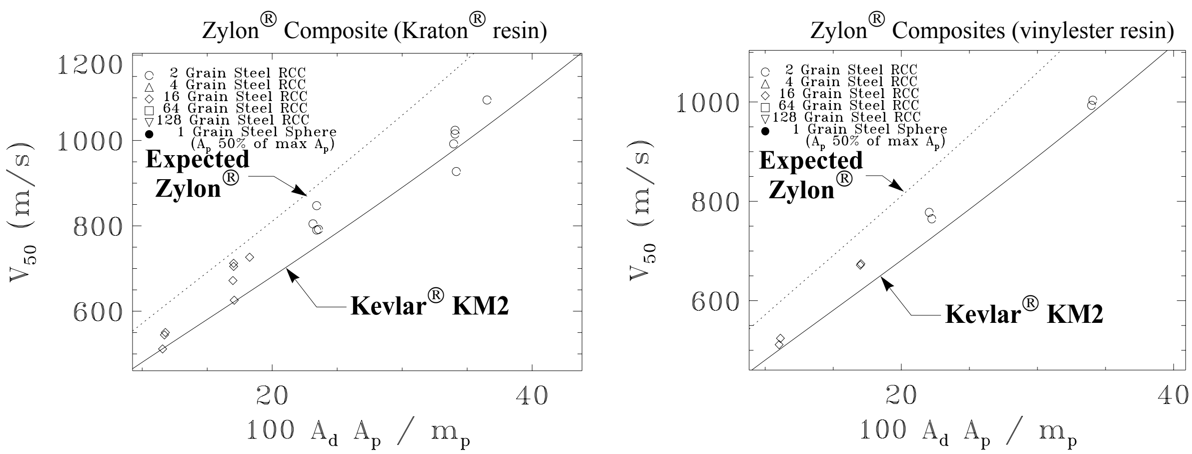

Fig. 6. V50 performance of Zylon® fabric-based composites with Kraton® and vinylester resins

ZYLON® UNIDIRECTIONAL COMPOSITES

Six-inch wide unidirectional tapes were prepared by fusing non-woven thermoplastic polyester sheet goods onto aligned and spread fibers; a basis weight of 115 g/m^2 (3.5 oz/yd^2) and a resin content of approximately 12 percent was used to prepare the unidirectional tapes.

Composites were prepared in a two-step process. In the first step, cross-plied unidirectional (0,90) sheet goods were prepared by fusing 6(6”x18”) unidirectional plies into an 18”x18” lamina. Fusing conditions used for this step were 149 °C, 1 bar (10 psi), 30 seconds. These lamina were further consolidated in a compression molding machine. Processing conditions included a temperature ramp to 149 °C at a consolidation pressure of 60 bar (900 psi), a 30 minute soak at 149°C and 900 psi, and a cooling cycle from 149 to 50 °C at 900 psi. Flat panels with areal densities as indicated in Table 4 were prepared.

V50 ballistic impact tests were conducted using 2-, 4-, and 16-, 64-grain right circular cylindrical steel projectiles and a 1-grain steel sphere. Results of the V50 tests are illustrated in Figure 7, and tabulated in Table 4. Additional testing of nominal 1.5 lb/ft^2 (7.2 kg/m^2) areal density targets from this material against a 124 grain 9 mm full metal jacket handgun projectile yielded partial penetrations up to 1815 ft/s striking velocity. AS indicated in Figure 7, impact performance of systems based on unidirectional Zylon® with a thermoplastic polyester resin was exceptional. In addition to the Kevlar® KM2 PVB/phenolic and expected Zylon® performance curves, the Kevlar® 29 PVB/phenolic and flat panel performance goal curves are plotted in Figure 7. Zylon® unidirectional systems performed at about the flat panel goal of 2/3 the weight of Kevlar® 29 PVB/phenolic systems with equal performance.

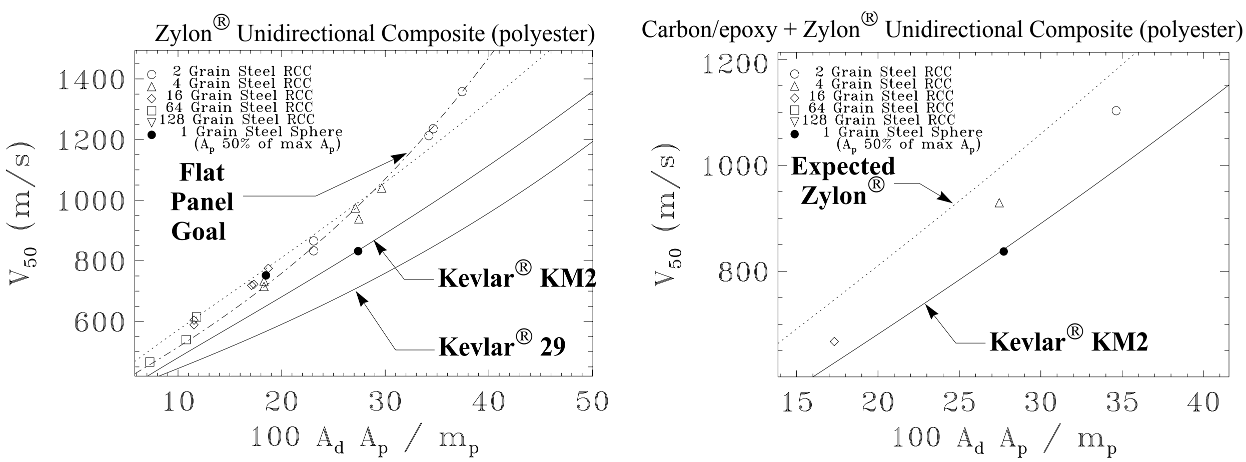

Fig. 7. V50 performance of Zylon® unidirectional composites with a thermoplastic polyester resin, and V50 performance of hybrid armor comprised of 1/3 carbon fiber with an epoxy resin and Zylon® unidirectional composites with a thermoplastic polyester resin

A Newport Adhesives and Composites carbon fiber unidirectional prepreg (150 g/m^2 fiber weight) with approximately 36% resin content toughened epoxy and using a Graphil 34-700 fiber having a tensile modulus of 34 Msi, and 650 ksi strength was used to prepare strikeface composites for a hybrid carbon fiber/Zylon® fiber composite panel. A single nominal 0.5 lb/ft^2 panel of carbon fiber reinforced epoxy was prepared for ballistic testing. Processing conditions for the carbon-epoxy composite included a temperature ramp to 121°C at a consolidation pressure of approximately 3.4 bar (50 psi), a 30 minute soak at 121°C and 50 psi, and a cooling cycle from 121 to 50 °C at 50 psi. A Zylon® composite with nominal areal density of 1.0 lb/ft^2 was processed on top of the cured carbon fiber-epoxy panel in a compression molding machine as a separate step. Processing conditions for the Zylon® composite included a temperature ramp to 149 °C at a consolidation pressure of 60 bar (900 psi), a 30 minute soak at 149 °C and 900 psi, and a cooling cycle from 149 to 50°C at 900 psi. V50 ballistic impact tests were conducted using 2-, 4-, and 16-grain right circular cylindrical steel projectiles. Results of the V50 tests are illustrated in Figure 7. The significant loss in V50 velocity with the incorporation of a carbon fiber/epoxy system is presumably indicative of the capacity of Zylon® armor to absorb appreciable strain energy at high striking velocities.

Table 4: Zylon® Unidirectional Flat Panel V50 Data

Areal Density (kg/m^2)	Projectile Type	V50 (m/s)			
		2-grain RCC	4-grain RCC	16-grain RCC	64-grain RCC
4.88	Steel	865.7	733.5	588.9	
4.88	Steel	832.9	715.2	604.2	466.2
7.23	Steel	1212.8	974.4	719.2	540.1
7.32	Steel	1235.8	938.3	722.5	
7.91	Steel	1358.2	1040.1	775.2	615.0

SUMMARY

Among the armor materials considered in this work, Spectra® with a vinylester resin and Zylon® unidirectional composites with a thermoplastic polyester resin system each offer potential weight savings for helmet applications. It is estimated that fragmentation protective armor systems based on Zylon® unidirectional materials will reduce the areal density of the ballistic component of these systems by approximately 25% over Kevlar® 29 composites at the same level of protection.

REFERENCES

1. Bass, C.R., Boggess, B., Bush, B., Davis, M., Chapman S., Harris, R., Rountree, M., Sanderson, E., Andrefsky, W., Adams, J., Monaui, W., Eklund, J., Ling, G., and Waclawik, S., Helmet Behind Armor Blunt Trauma Injury Risk, U.S. Army Soldier and Biological Chemical Command Technical Report, in review (2003).
2. van Hoof, J., Cronin, D.S., Worswick, M.J., Williams, K.V., and Nandlall, D. Numerical Head and Composite Helmat Models to Predict Blunt Trauma, 19th International Symposium of Ballistics, Interlaken, Switzerland (May 2001)
3. Cunniff, P. M., "Dimensionless Parameters for Optimization of Textile-Based Body Armor Systems", Proceeding of the 18th International Symposium on Ballistics, San Antonio, TX (Nov 1999)