Low Velocity Ballistic Behavior of Continuous Filament Knit Aramid

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Abstract

The ballistic perforation response of knits formed from continuous filament aramid is reported and compared to conventional armor textiles and commodity fabrics. The ballistic experiments consist of 6.0-mm-diameter glass spheres impacted into gelatin-backed targets with areal densities from 200-1000 g/m². These ballistic experiments are complemented with quasistatic reverse-perforation experiments to gain insights into deformation and failure for these materials. In-plane stretch experiments are also performed to quantify modulus and strain-to-failure. The results show that, while the ballistic performance of traditional woven textiles is generally superior to knitted aramids, knits formed from continuous filament aramid are significantly better than knits formed from staple yarn. Knitted structures are limited by two main factors: failure of a single yarn tends to lead to catastrophic deconstruction and perforation, and the low in-plane modulus of knits leads to poor lateral stress transfer and energy distribution during higher speed impact. Importantly, however, knits provide significantly more reversible

elongation with less elastic resistance compared to other structures, such as woven textiles, making them well-suited for wearable protection in which comfort is critical. The results also show that continuous filament knits can be produced with commercial manufacturing equipment, and that barriers composed of few layers of high-denier yarn knits likely provide more efficient ballistic resistance than equivalent weight barriers composed of many layers of low-denier yarn knits.

1. Introduction

The majority of ballistic textiles research focuses on woven fabrics, the most common architecture used in ballistic barriers such as body armor [1, 2]. The woven structure of these textiles are well-suited for ballistics for a number of reasons including: low-crimp woven yarns are relatively straight, and therefore load during ballistic impact without significant backface deformation; yarns can be closely packed, limiting lateral yarn motion during ballistic loading; and, for typical woven architectures and projectile geometries, projectile loads can be shared amongst multiple yarns simultaneously, so that multiple yarns must be failed in order for a projectile to penetrate a woven fabric barrier.

Woven fabrics are not stretchable along their principal axes [3]. For many ballistic barriers, such as torso body armor or turbine blade containment systems, stretch is not a primary requirement. However, for some applications it is beneficial to have an armor material that is stretchable, for example for close-fitting protective garments, ballistic shorts, and extremity armor. Stretchable textiles enable greater freedom of motion, and therefore comfort, than comparable woven textiles.

Knits are a textile architecture with inherently high stretch, due to the looped configuration of the comprising yarns (Fig. 1) [4, 5]. The two principal axes of the knit structure are referred to as courses (side-by-side series of loops) and wales (interlocked head-to-tail series of loops). The simplest and most common structure is a single jersey knit, in which each course is composed of a single yarn. Although the quasistatic mechanics of knits have been the topic of considerable experimental [6, 7] and theoretical [8, 9] investigation, as well as limited computational simulation [10, 11], little systematic data on the ballistic performance of knits has been reported. One early study on unbacked, edge-clamped nylon knits, using lead pellets fired at an impact energy of 9.4 J and target areal densities of 80-120 g/m² (gsm), found that the knit ballistic performance was only slightly below that of a comparable plain-woven nylon textile [12]. A subsequent study [13] compared woven and knit Kevlar textiles, impacted with steel cylindrical projectiles at higher energies (125 J) and areal densities (1000-5000 gsm), and found that the knits required more mass (approximately 2.5×) to achieve the same ballistic performance level as a woven textile. Studies on knitted high performance yarns, at lighter areal densities (200-1000 gsm) appropriate for extremity armors or other close-fitting protective garments, have not been reported. Some research has indicated that knitting high performance yarns could lead to degradation in yarn tensile properties during the knitting process [14], which could limit barrier performance.

In this study, the ballistic behavior of continuous filament, knitted aramids (CFKAs) is compared with conventional armor textiles and commodity fabrics. CFKA materials include knits created using a commercial knitting loom, allowing for a systematic comparison of architecture parameters while demonstrating the manufacturability of continuous filament knits. Commodity fabrics include knitted staple yarn aramids, in which the yarns are composed of

short, entangled filaments, in contrast to the continuous filaments of the CFKA material. Elongation experiments are performed to characterize in-plane elastic modulus and strain-to-failure for a subset of the textiles, and quasistatic reverse perforation experiments provide additional insights into the mechanistic progression of failure in knits compared to other materials.

2. Experimental

2.1 Materials

2.1.1 Baseline materials

Table 1 lists all of the baseline materials evaluated. Baseline fabrics included commodity textiles, which we define as textiles that are not normally used to provide ballistic protection, and armor textiles. Figures 2 and 3 show images of the fabrics at 10× and 250× magnification, respectively.

Army Combat Uniform (ACU) textile is a ripstop woven material constructed from a fiber blend of staple rayon, para-aramid, and nylon fibers. It is similar to the fabric used in the U.S. Army battle dress uniform (BDU). Silk fabric tested in this study was a single jersey knit. Silkworm-derived silk is considered a continuous filament yarn because the fibers are significantly longer than those typically observed in a natural staple yarn like wool or cotton, although fiber ends are evident within the textile. Light KK and Heavy KK are two staple Kevlar knits used in a variety of consumer goods, with a typical filament length of 20-50 mm (based on manual separation and inspection). The final commodity fabric was single jersey polyester knit. Polyester is representative of typical lightweight, stretchable, synthetic

commercial comfort fabrics. Like silk, polyester is nominally a continuous filament knit, although some fiber ends are apparent when the knit is inspected closely.

K706 is a woven ballistic fabric constructed from true continuous filament (no fiber ends are apparent) 600d KM2 Kevlar yarns, and is representative of a torso body armor textile.

Three ballistic felts were also evaluated. Hydro-entangled Dyneema (HED) is an experimental material made from ultra-high molecular weight polyethylene (UHMWPE). ArmorFelt is a commercially produced hybrid felt, composed of both aramid and UHMWPE filaments. TexTech is a commercial textile containing both felted and woven aramid material layers. The material layers are held together with needle punched staple aramid yarns. TexTech fabric is notably heavier than the other materials tested.

2.1.2 Continuous filament knits

Table 2 shows properties of the continuous filament knit aramids (CFKA) evaluated. Prototype CFKA was first produced on a lab scale circular knitting machine, the Lawson Hemphill Fiber Analysis Knitter Sampler (FAK-S), using continuous filament 600d KM2 Kevlar yarns. Single-jersey CFKA tubes 7-cm in diameter were fabricated and were cut to create approximately 20-cm-wide strips for ballistic tests. Figure 4 compares the Prototype CFKA and Heavy KK staple knit. The high population of fiber ends is clearly visible in the commodity product, while few fiber ends are evident in the CFKA material.

Following proof-of-concept testing, four single jersey, CFKA fabrics were knit at a pilot-scale using a commercial circular knitting machine at the Polartec, LLC production facility in Lawrence, MA. Each sample was knit from one of four potential KM2 yarn deniers: 400d, 500d, 600d, and 850d, with all knits having similar numbers of courses and wales per unit length.

Figure 5 shows micrographs of the pilot CFKAs. All fabrics were knit on an 18 cut, 76.2 cm cylinder knitting machine with 45 input feeds. Machine settings were adjusted to maintain similar course and wale counts between fabrics. Extracted yarn tenacity testing (not shown) indicated that yarn strengths dropped by 10-25% due to the knitting process. Compared to the prototype CFKA, the pilot CFKA knits have a higher number of courses and wales per unit length.

2.2 Test methods

2.2.1 Tensile testing

Tensile testing is reported for ACU, silk, Heavy KK, K706, ArmorFelt, and Prototype CFKA materials. Rectangular strips $25.4\text{ cm} \times 7.62\text{ cm}$ of each fabric were cut from bulk, with the sample edges parallel to the warp and weft directions for the woven materials, and parallel to the courses and wales for the knit materials. Both ends of each strip were folded over 2.54 cm and sewn to increase the thickness of the fabric in the gripping region, thus creating specimens with $15.2\text{ cm} \times 7.62\text{ cm}$ rectangular gage areas. To perform the test, fabric specimens were loaded into an MTS Synergie load frame using mechanical screw grips, with the long specimen direction parallel to the load path. A 5 kN load cell was used for the K706, ArmorFelt, and ACU samples, while a 500 N load cell was used for the silk, Heavy KK, and CFKA materials. Fabrics were pulled at a rate of 16 mm/min.

2.2.2 Ballistic resistance characterization

The projectile used in ballistic tests was a glass sphere with a nominal diameter and weight of 6.0 mm and 0.28 g respectively (BB Bastard, Toronto, Canada). This projectile is

used, rather than a more typical steel projectile, to better match the size and mass of a gravel particle that would be launched by a buried explosive. A helium driven, smooth bore gas gun was used to accelerate the projectiles. Two light chronographs made independent measurements of projectile velocity, with the average velocity value reported.

Two series of ballistic experiments were performed: the first series compared baseline materials to the prototype CFKA, while the second series evaluated the pilot-scale materials. As will be discussed in more detail below, the differences in test conditions were due to practical concerns (such as limited material availability), but are believed to produce comparable data sets. Due to the low areal densities of the present targets, conventional ballistic test methods (e.g. MIL-STD-662, NIJ Standard 0101.06) intended for evaluation of torso body armor were not appropriate.

In the first series each target was subject to nine ballistic impacts. Impact locations were marked according to a predetermined, staggered impact pattern. To simulate realistic backing conditions, targets were wrapped around synthetic gelatin cylinders that measured approximately 15.2 cm in diameter and 30.5 cm in height. The gelatin is based on a physically associated polymer mixed with a low volatility non-aqueous solvent, formulated to satisfy the calibration standards for 20% ordnance gelatin [15, 16]. Target dimensions were approximately 46.5 cm $\times$ 30.5 cm. Velcro strips were sewn to the target edges to secure it around the gelatin cylinder, with the targets pre-tensioned slightly to eliminate any slack and ensure a close fit to the gel backing. Shot velocities for each target were selected to achieve a mixture of penetrating and non-penetrating responses. V_{50} limits were calculated using maximum likelihood estimation to fit the data with a cumulative distribution function for a normal distribution.

The second test series was conducted similarly to the first test series, with a few modifications. The number of shots per tests was increased to 15 and synthetic gelatin was replaced with natural 20% ordnance gelatin, wrapped with a single layer of commercial 12.5- μ m cling wrap polyethylene film to prevent moisture intrusion into the targets. Additionally, targets were affixed to the cylinder using nylon straps. Finally shot speed selection followed the method prescribed by a modified Langlie technique [17].

The differences in test conditions for the two ballistic test series (shots per target, synthetic versus natural gelatin, target mounting) are relatively minor. To ensure that the two test series produce comparable data, experiments on five silk, ACU, Light KK, and Heavy KK targets were performed as part of both the first test series and second test series. The V_{50} values were found to differ between test series, on average, by 3%. Therefore, all results from both test series can be reasonably compared as a single data set.

A baseline V_{50} for the ballistic gelatin, without a fabric target, was measured by defining a "penetration" as an impact in which the projectile remained embedded in the cylinder. This gelatin V_{50} was found to be 130 m/s for the synthetic gelatin cylinder (first test series), and 107 m/s for the natural gelatin cylinder wrapped with cling wrap (second test series). For simplicity, we use the average value, 119 m/s, as a representative gel penetration velocity for benchmarking target performance.

2.2.3 Quasistatic puncture

Quasistatic puncture tests were conducted on ACU, Heavy KK, K706, ArmorFelt, 400d SJ, and 850d SJ samples. Samples were tested in a reverse puncture configuration so that the projectile position remained fixed relative to ground, simplifying imaging by providing a

common frame of reference for both the projectile and the video camera (Figure 6). A glass sphere was epoxied to the end of a steel rod and threaded into a fixed load cell. Fabric coupons were clamped into a square fixture with inner aperture of $10.2\text{-cm} \times 10.2\text{-cm}$ that was subsequently mounted on the crosshead using C-clamps. As the crosshead moved downward at 30 mm/min, the fabric was slowly stretched over the projectile until punctured.

With the aid of a high speed camera it was possible to record images of the puncture event. A Photron Fastcam SAS RV camera was used to take pictures at 100,000 fps with a $1/517000$ s shutter speed. The recording timeframe consisted of 70% pre-trigger to ensure the event was captured. The load cell output was recorded on a Tektronix DPO71245C oscilloscope. When the load suddenly dropped due to puncture, the oscilloscope output a 2.5 V pulse to the Photron camera initiating its trigger. The sample was illuminated using two Dedocool 250 W lamps each powered with a CoolT3 power supply.

3. Results

3.1 Tensile testing

Figure 7a shows the raw load versus displacement data from tensile testing. The load data is presented on a log axis to capture all sample behaviors, from the very high loads (> 1000 N) generated by the K706 samples to the very low loads (1-10 N) produced by the CFKA material. The K706 and ACU samples show loads to failure, while for other samples loading was stopped prior to failure. It is evident from the data that the K706, ArmorFelt, and ACU textiles are considerably more resistant to tensile elongation compared to the knitted materials.

Figure 7b presents the tensile data as specific stress versus true strain, where specific stress is calculated by normalizing the fabric load by the product of initial sample width and areal

density, and true strain is $\ln(L/L_o)$ where L_o is the initial sample length and L is the elongated sample length. Also shown inset in the figure is a tabulation of the specific linear modulus of each sample, calculated over the strain range of 1-3%. The modulus data shows that the K706 textile is approximately $10^3 - 10^4 \times$ stiffer in-plane compared to the knits, the ACU fabric is approximately 10-100 $\times$ stiffer than the knits, and the ArmorFelt is roughly 10 $\times$ stiffer than the CFKA and silk knits.

3.2 Ballistic characterization

The V_{50} performance of all targets is presented in Table 3. Figure 8 shows the results from baseline materials and prototype CFKA, with dashed lines to provide guides for interpolating the overall performance of different material classes. Also shown in the figure is the nominal V_{50} value for the ballistic gel alone. Micrographs of failure zones are presented in Figure 9. Images are of the lowest velocity, penetrating impact.

Commodity fabrics provided the lowest perforation resistance on a per weight basis, and all commodity fabrics collapsed onto a single performance curve. The results indicate that staple aramid offers no ballistic advantage over comfort fabrics such as silk and polyester. Based on these results, the ballistic perforation resistance of these materials correlates most directly to the areal density of the targets, and does not appear to be strongly influenced by details of fabric construction or filament mechanical properties. Woven K706 provided significantly better perforation resistance than the commodity materials, as would be expected since this textile has been engineered for ballistic protection. The failure region for K706 shows evidence of windowing (in-plane yarn spreading and separation) and filament failure.

The CFKA prototype better perforation resistance than the commodity materials, but not as well as woven K706. At 270 m/s the prototype CFKA V_{50} is approximately 40% greater than that of commodity targets and only 7% below K706. CFKA and Light KK targets are both single jersey knits with similar areal densities. The sizable difference in performance between the two materials suggests that staple yarns degrade ballistic performance, and significantly better knit ballistic performance can be achieved by using continuous filament yarn. CFKA failure shows a distinct, local yarn failure with closely grouped fiber ends, unlike the commodity fabrics which tend to show a less distinct failure location.

Of the baseline materials, felts demonstrated the highest mass normalized V_{50} values. HED and ArmorFelt perform similarly over the range of areal densities tested here. Felting did not appear to enhance the ballistic properties of the TexTech fabric. Its V_{50} was 414 m/s at 844 gsm which is approximately the performance that would be expected of K706 at that areal density. Due to the inherent entangled nature of felts it is difficult to identify if perforation is due to fiber failure or simply fiber untangling and separation of pre-existing fiber ends for this textile.

The performance of the four pilot CFKA fabrics is presented in Figure 10. Data from the commodity knits and the CFKA prototype from the first test series are also included in the figure for comparison. There is a positive correlation between yarn denier and V_{50} . The Pilot 400d and Pilot 500d samples performed approximately the same as commodity knits. However, the Pilot 600d and Pilot 850d fabrics have appreciably better ballistic behavior. It is noteworthy that the pilot CFKAs underperformed relative to the prototype CFKA, which may be due to the differences in knit geometry or yarn damage induced by the different knitting machinery.

3.3 Quasistatic puncture

Figure 11 shows load versus displacement for the quasistatic puncture experiments, and Table 4 shows the peak puncture load values, energy to failure, and load and energy values normalized by the textile areal density. It is evident that the commodity materials (ACU, Heavy KK, and Polyester) show the lowest puncture values while the K706, ArmorFelt, 400d SJ and 850d SJ samples show significantly higher puncture loads. All samples failed catastrophically and suddenly, with the exception of the ArmorFelt sample which showed a long and gradual load reduction during failure. The polyester undergoes significantly higher displacement to failure compared to the other materials. Figure 12 shows images of three of the samples near their failure point. The K706 sample shows much less deformation compared to the polyester and ArmorFelt samples, with the ArmorFelt showing prevalent fiber sliding and unwinding after the peak load point.

Figure 13 shows high speed images for three of the knit specimens: Heavy KK, 400d SJ, and 850d SJ. The images indicate that for both the staple knit and CFKA the puncture process begins after a single yarn loop breaks. Following loop failure the hole expands and stretches over the projectile causing a combination of filament failure and windowing. It appears that the hole grows more quickly in the CFKAs, compared to the staple knit, likely due to the higher forces on the CFKA membrane at failure.

4. Discussion

The ballistic test results show that all commodity textile data collapses onto a single V_{50} versus areal density performance curve. The uniformly low ballistic behavior of these materials is most likely driven by their low effective yarn strengths. The silk and polyester knits are

continuous filament, but are inherently low strength fibers (the strength of Kevlar filaments, for example, are likely to be roughly 10× higher than silk [18]). The ACU, Light KK, and Heavy KK may be composed of higher strength filaments (nylon and Kevlar), but as staple materials their yarn strength will be driven by filament interactions (twist and friction) rather than merely the ideal filament strength [19, 20].

Comparing the staple aramid knits (Light KK and Heavy KK) versus the high denier (600d and 850d) CFKA knits, it is evident from both quasistatic puncture and ballistic data that continuous aramid fibers lead to better performance compared to entangled, short aramid fibers. The fact that yarn tenacity decreased somewhat after knitting suggests that, if details of the knitting process could be addressed to minimize yarn strength reductions, then knit ballistic resistance could increase further. Yarn tenacity could also explain why the prototype CFKA material slightly outperformed the pilot-scale CFKA, since the prototype loom operated at a slower speed and may have been more gentle in handling the yarns. The lower number of wales and courses per unit length for the prototype CFKA could also contribute to the difference in performance, although systematic experimentation would be required to validate this trend.

For the pilot materials, the knits composed of heavier denier yarns (600d and 850d) provided higher ballistic resistance than the knits composed of lower denier yarns (400d and 500d). In fact, the low denier pilot CFKA knits did not show a measureable increase in ballistic performance relative to the staple knits. This contrast between high and low denier knits can be explained by considering the failure images during quasistatic puncture of various knits in Fig. 11, which shows that the failure of a single yarn triggers an unraveling of the knit structure that enables puncture. A single knit layer composed of heavy yarns will provide high resistance, as high loads are necessary to fail a single, high denier yarn. A multi-layer knit target composed of

finer yarns can provide equivalent resistance only if the membrane loads are being shared evenly between the layers and amongst the yarns. During realistic ballistic loading, variations in layer tension, orientation, boundary conditions, etc. are likely to lead to non-uniformities in yarn loading. If these non-uniformities lead to failure of any single yarn within the multi-layer assembly, a cascading series of failures and unraveling will occur to catastrophically fail the entire target assembly. Therefore knits can be considered "weakest link" architectures in which their ultimate performance is driven by the weakest material element in the assembly, so that a single-layer knit composed of heavy yarns is likely to perform better than a weight-matched target of multiple layers of a lower areal density knit composed of finer yarns. A caveat to this hypothesis is that the data does not show a continuous increase in per-mass ballistic performance with increasing yarn denier, i.e. there appears to be a significant difference in performance for 600d versus 500d pilot knits, but little difference in behavior between 600d and 850d pilot knits. A more systematic study is required to separate the specific roles of yarn denier, architecture, and knitting process history on ballistic perforation. For example, in the present pilot knits, the course and wale spacing remains relatively constant for all yarn deniers; perhaps a more systematic trend in perforation resistance would be observed if the course and wale sizes increased proportionally with yarn denier.

Comparing the CFKA and woven K706 textile, both the puncture data and ballistic data show that the woven architecture provides superior perforation resistance. This trend is most likely due to the fact that the woven architecture can survive multiple yarn failures before experiencing catastrophic failure, while the knits are likely to unravel after a single yarn failure. A more subtle trend is apparent by noting that the difference in performance between K706 and CFKA increases with areal density. This trend indicates that knits may perform more

comparably to wovens at low areal densities and velocities, while losing efficiency as velocity and energy increase. This behavior is consistent with prior work [12-13], and can be explained by considering the low in-plane elastic modulus, and therefore stress wave propagation speed, for knits compared to wovens (Fig. 7). As impact velocity increases, the knit transmits loads over a more limited lateral distance compared to wovens, resulting in less material volume available for energy absorption and a lower per-mass ballistic performance. These results suggest that conventional knits, as studied in this manuscript, are best suited for low-velocity ballistic events and low-density armors.

Interestingly, the felts provided the best overall ballistic efficiency. Prior comparisons of felts and wovens by Liable and Henry [21, 22] showed that nylon felts provided significantly better ballistic efficiency at velocities up to 400 m/s, but suggested that wovens become more efficient at higher velocities. They attributed this behavior to the fact that, at low velocities, the felts undergo significantly more deformation than the wovens and therefore can absorb energy over longer time periods. In contrast, at high velocities, the very low in-plane and transverse wave speeds of the felts compared to wovens localized the failure and limited the volume of material participating in the ballistic interaction. These rate-dependent mechanisms are analogous to those observed in the comparative behavior of knits and wovens.

Some additional insight can be gained by plotting the ballistic data versus the quasistatic puncture data. We define a "specific ballistic energy" $\bar{U}$ (units of J/gsm) as

$$\bar{U} = \frac{m_p (V_{50}^2 - V_{50, \text{gel}}^2)}{2\rho_A}$$

where V_{50} and $V_{50, \text{gel}}$ are the V_{50} values of the target and the gel block alone (using the average value measured for the natural and synthetic gelatin cylinders), respectively, m_p is the projectile mass, and ρ_A is the areal density of the target. The specific ballistic energy represents a mass-normalized ballistic energy absorption capability of the target. Values are tabulated in Table 4, using the lowest areal density ballistic data available, for materials that were also evaluated for quasistatic puncture resistance. Also tabulated is the puncture energy to failure, normalized by the areal density of the puncture samples.

Figure 14 plots specific ballistic energy versus specific puncture energy. Generally, increasing puncture energy correlates with increasing ballistic energy. For the ArmorFelt and knitted materials (Polyester, Pilot 400d, and Pilot 850d) the puncture energies are roughly 2-3× higher than the ballistic energies. These high puncture energies for these materials are due to their high deformations to failure under quasistatic conditions; under ballistic conditions, loading and failure will be more localized and its mechanical efficiency will be reduced.

Figure 14 also shows that while Pilot 850d and Pilot 400d CFKA show comparable specific puncture energies, the Pilot 850d provides significantly higher ballistic efficiency. This result supports our earlier "weakest link" hypothesis. Since the quasistatic experiments were performed on single layer materials, layer-to-layer load sharing is not a concern and the normalized puncture energies are comparable between the 850d and 400d materials. At higher speeds and comparing a multi-layer material 400d target to a single-layer 850d target, the lower relative performance of the 400d target suggests inefficient load-sharing between the plies and possibly between yarns. Additional testing, supported by numerical simulations [23], should provide further insight into these considerations.

Finally, returning to the tensile testing data (Fig. 7), the elastic modulus trends quantify what is immediately apparent when manually handling the various textiles: the knits are easy to stretch, while the woven fabrics are essentially un-stretchable along their principal yarn directions. The felts provide some extensibility, but after small strains this extension is mostly irreversible. For this reason, modern compression garments and athletic wear, including athletic shoes, are composed of knitted textiles. Similarly, to meet emerging needs for close-fitting ballistic undergarments and extremity protection, only knits are universally suitable, while wovens, felts, and other non-stretchable materials would only be practical as patches in garment areas that are subject to low stretch. Of the knits evaluated in this study, the CFKA materials provide the best combination of high stretchability and good ballistic efficiency.

5. Conclusions

This study provides the first systematic evaluation of the ballistic barrier properties of knits composed of high performance, continuous filament yarns. The results show that the continuous filament knitted aramids provide a unique combination of stretchability and mass-efficient perforation resistance relative to commodity materials, woven ballistic textiles, and ballistic felts. The data also indicates that barriers composed of fewer, heavier knit layers should provide performance superior to equal mass barriers composed of a higher number of lighter knit layers.

At present, only continuous knit aramids have been evaluated. Knits composed of other high performance continuous filament materials such as UHWMPE should also provide good ballistic performance. Similarly, the present study only considered one knit style, single jersey. The diverse range of additional knit styles available suggest that further optimization of

357 performance is possible, perhaps to include the creation of a set of materials with tradeoffs in
358 stretch versus ballistic performance. Finally, finite element models of ballistic impact into
359 knitted materials are under development to provide predictive design capabilities for future
360 knitted ballistic materials.

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References

1. B. A. Cheeseman and T. A. Bogetti. "Ballistic impact into fabric and compliant composite laminates." *Comp. Structures*. v61 p161-173. 2003.
2. N. V. David, X.-L. Gao, and J. Q. Zheng. "Ballistic resistant body armor: Contemporary and prospective materials and related protection mechanisms." *Appl. Mech. Rev.* v62 n5 p050802-1 - 050802-20. 2009.
3. Z. Dong, J. M. Manimala, and C. T. Sun. "Mechanical behavior of silica nanoparticle-impregnated Kevlar fabrics." *J. Mechanics Materials Structures*. v5 n4 p529-548. 2010.
4. Image generated by P. Justin McKee, U.S. Army Research Laboratory. Personal communication. 2015.

5. R. Postle. "Structural mechanics of knitted fabrics for apparel and composite materials." J. Textile Institute. v92 n3 p80-90. 2001.
6. B. M. MacRory and A. B. McNamara. "Knitted fabrics subject to biaxial stress - an experimental study." Textile Research Journal. v37 n10 p908-911. 1967.
7. B. M. MacRory, J. R. McCraith, and A. B. McNamara. "Experimental investigation of the biaxial load-extension properties of plain, weft-knitted fabrics." Textile Research Journal. v47 n4 p233-239. 1977.
8. R. Postle and D. L. Munden. "Analysis of the dry-relaxed knitted-loop configuration. Part I: Two-dimensional analysis." J. Textile Institute. v58 n8 p329-351. 1967.
9. W. J. Shanahan and R. Postle. "A theoretical analysis of the plain-knitted structure." Textile Research Journal. v40 n7 p656-665. 1970.
10. A. U. Loginov, S. A. Grishanov, and R. J. Harwood. "Modelling the load-extension behavior of plain-knitted fabric: Part III: Model implementation and experimental verification." J. Textile Institute. v93 n3 p251-275. 2002.
11. J. Kaldor, D. James, and S. Marschner. "Simulating knitted cloth at the yarn level." ACM Trans. Graph. v27 n3 p61-1 - 65-2. 2008.
12. J.W.S. Hearle, and M. A. I. Sultan. "Research on a basic study of the high-speed penetration dynamics of textile materials." Manchester (UK): University of Manchester Institute of Science and Technology. Available from DTIC, Fort Belvoir, VA: ADA003504. May 1974.
13. C. R. Cork and P. W. Foster. "The ballistic performance of narrow fabrics." Int. J. Impact Eng. v34 p495-508. 2007.
14. K.W. Lau and T. Dias. "Knittability of high-modulus yarns." J. Textile Institute. v84 n2 p173-190. 1994.
15. D. T. Casem, A. J. Dwivedi, R. A. Mrozek, and J. L. Lenhart. "Compression response of a thermoplastic elastomer gel tissue surrogate over a range of strain-rates." Int. J. Solids Structures. v51 n11-12 p2037-2046. 2014.
16. Z. I. Kalcioğlu, R. Mrozek, R. Mahmoodian, M. R. VanLandingham, J. L. Lenhart, and K. J. Van Vliet. "Tunable mechanical behavior of synthetic organogels as biofidelic tissue simulants." J. Biomechanics. v46 n9 p1583-1591. 2013.
17. T. H. Johnson, L. Freeman, J. Hester, and J. L. Bell. "A comparison of ballistic resistance testing techniques in the Dept. of Defense." IEEE Access. v2 p1442-1455. 2014.

18. I. Krasnov, I. Diddens, N. Hauptmann, G. Helms, M. Ogurreck, T. Seydel, S. S. Funari, and M. Muller. "Mechanical properties of silk: interplay of deformation on macroscopic and molecular length scales." *Phys. Rev. Lett.* v100 n048104 p1-4. 2008.
19. N. Pan. "Prediction of statistical strengths of twisted fibre structures." *J. Mat. Sci.* v28 n22 p6107-6114. 1993.
20. S. L. Phoenix. "Statistical theory for the strength of twisted fiber bundles with applications to yarns and cables." *Textile Research Journal.* v49 p407-423. 1979.
21. R. C. Laible and M. C. Henry. "A review of the development of ballistic needle-punched felts." U.S. Army Natick Laboratories. Report No. TS-167 70-32-CE. Available from DTIC, Fort Belvoir, VA: AD0707918. Oct. 1969.
22. R. C. Laible and M. C. Henry. "Development of needle-punched felts." *American Dyestuff Reporter.* v60 n4 p36-41. 1971.
23. P. Justin McKee, A. C. Sokolow, A. K. Dwivedi, and E. D. Wetzel. "Finite element simulation of ballistic impact on single jersey knit fabric." *Proc. of Fiber Society 2014 Fall Meeting and Technical Conference, Fibers for the Future.* Philadelphia, PA. October 22-24, 2014.

Tables

Table 1: Baseline extremity protection materials. Materials above the dashed line are considered "commodity" textiles, while those below the dashed line are considered ballistic textiles. Areal density units of "gsm" are g/m^2 .

Sample name	Description	Part number	Source	Areal density (gsm)
ACU	"Improved Defender M" Fire Resistant ACU fabric	-	Tencate (Almelo, Netherlands)	220
Silk	knitted Jersey silk	-	NY Fashion Center (New York City, NY)	165
Light KK	"light" knitted staple Kevlar	145KV30	Green Mountain Knitting (Milton, VT)	225
Heavy KK	"heavy" knitted staple Kevlar	437KV17	Green Mountain Knitting (Milton, VT)	328
Polyester	knitted polyester	-	Jo-Ann Fabrics (Bel Air, MD)	96
K706	woven 600d KM2 Kevlar	Style 706	JPS Composites (Anderson, SC)	180
HED	hydroentangled Dyneema felt	-	UK Ministry of Defense	200
ArmorFelt	Armorfelt, hybrid aramid/PE felt	-	Kennon Covers Inc. (Sheridan, WY)	250
TexTech	hybrid felt / woven fabric	9010	TexTech Industries (Portland, ME)	844

Table 2: CFKAs evaluated. The prototype CFKA was produced on a lab-scale circular knitting machine, while the knits below the dashed line were produced using a production circular knit machine.

Sample name	Yarn size	Stitch meter	Wales	Courses	Areal density
-	(den)	(in/rev)	per cm	per cm	(gsm)
Prototype CFKA	600	-	5.0	9.8	200
Pilot 400d	400	270	8.7	13	219
Pilot 500d	500	275	8.4	12	288
Pilot 600d	600	275	8.9	10	338
Pilot 850d	850	325	8.8	12	433

Table 3: Ballistic performance (V_{50} in m/s) for all fabrics. Materials above the first dashed line are commodity textiles, while materials between the two dashed lines are ballistic textiles. All materials above the solid line were evaluated according to the first, 9-shot test protocol, while materials below the solid line were evaluated according to the second, 15-shot test protocol.

Material	Number of plies					
	1	2	3	4	6	8
ACU	-	205	-	-	-	-
Silk	-	190	-	233	-	-
Light KK	-	213	-	-	-	-
Heavy KK	192	240	-	-	-	-
Polyester	-	-	-	198	-	230
K706	-	291	-	-	460	-
HED	298	367	403	-	-	-
ArmorFelt	327	410	-	-	-	-
TexTech	414	-	-	-	-	-
Prototype CFKA	-	270	-	-	-	-
Pilot 400d	-	205	233	-	-	-
Pilot 500d	201	228	-	-	-	-
Pilot 600d	231	266	-	-	-	-
Pilot 850d	245	274	-	-	-	-

Table 4: Peak force, energy to failure, and areal-density-normalized values from puncture testing. Also tabulated, for comparison, is ballistic energy at V_{50} normalized by the target areal density, based on the lowest areal density ballistic experiments for each sample.

Material	Puncture force (N)	Specific puncture force (N/gsm)	Puncture energy (J)	Specific puncture energy (mJ/gsm)	Specific ballistic energy (mJ/gsm)
ACU	206	0.94	1.2	5.4	8.9
Heavy KK	236	0.72	1.4	4.1	9.7
Polyester	122	1.27	2.4	24.5	9.2
K706	897	4.98	5.9	32.8	27.4
ArmorFelt	1092	4.37	23.1	92.3	52.0
Pilot 400d	867	3.96	4.9	22.5	8.9
Pilot 850d	1357	3.13	9.7	22.4	14.8

Figures

Figure 1: Single jersey knit structure [4].

Figure 2: Micrographs of evaluated fabrics at 10 $\times$ magnification. Scale bars at 5 mm. (a) ACU, (b) K706, (c) Silk. (d) Light KK, (e) Heavy KK, (f) Polyester, (g) HED, (h) ArmorFelt, and (i) TexTech.

Figure 3: Micrographs of evaluated fabrics at 250 $\times$ magnification. Scale bars at 200 μ m. (a) ACU, (b) K706, (c) Silk. (d) Light KK, (e) Heavy KK, (f) Polyester, (g) HED, (h) ArmorFelt, and (i) TexTech.

Figure 4: Comparison of (a) Heavy KK staple knit and (b) CFKA prototype. (c) Micrograph of Prototype CFKA at 250× magnification.

Figure 5: Pilot knits with varying yarn linear densities of (a) 400d, (b) 500d, (c) 600d, and (d) 850d.

(a)

(b)

Figure 6: Quasistatic puncture apparatus (a) photograph and (b) schematic.

(a)

(b)

Figure 7: Tension testing results. (a) Load versus displacement, and (b) specific stress versus true strain, with inset table of estimated specific modulus values for each sample.

Figure 8: Ballistic performance of baseline materials and Prototype CFKA. Dashed lines are guides to the eye.

Figure 9: Micrographs of failure regions. (a) ACU, (b) Silk, (c) Light KK, (d) Polyester, (e) K706, (f) HED, (g) ArmorFelt, (h) TexTech, and (i) Prototype CFKA. (The blackness in the impact region is residual ink from marking the shot location prior to testing.) Heavy KK (not shown) is similar in appearance to Light KK.

Figure 10: Ballistic performance of pilot CFKA materials. Lines are guides to the eye.

Figure 11: Force curves for quasistatic puncture experiments on single-layer targets. For all samples not including ArmorFelt, data is shown up until the point of failure, after which the load drops rapidly suddenly to a low value. For ArmorFelt, failure is more gradual. The load noise prior to failure for Heavy KK, K706, 400d SJ, and 850d SJ samples is due to multiple premature high speed camera triggering events, resulting in a pause in the experiment and subsequent stress relaxation while the triggers were reset.

(a)

(b)

(c)

Figure 12: Comparison of fabrics near failure during quasistatic puncture testing. (a) K706, (b) ArmorFelt, and (c) polyester.

Figure 13: High speed video images during quasistatic puncture testing for (a) Heavy KK, (b) Pilot 400d CFKA, and (c) Pilot 850d CFKA knits.

Figure 14: Specific ballistic energy versus specific puncture energy for select targets. Dashed line indicates trend for specific ballistic energy equal to specific puncture energy.

Continuous filament knitted aramid (CFKA)