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Low velocity ballistic behavior of continuous filament knit aramid

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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 to 1000 g/m^2. 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.

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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 among 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]. 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 [5,6] and theoretical [7,8] investigation, as well as limited computational simulation [9,10], little systematic data on the ballistic performance of knits have 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/m^2 (gsm), found that the knit ballistic performance was only slightly below that of a comparable plain-woven nylon textile [11]. A subsequent study [12] 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

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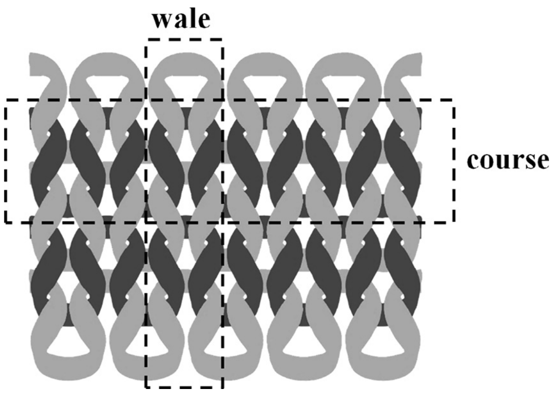

Fig. 1. Single jersey knit structure (image generated by P. Justin McKee, U.S. Army Research Laboratory).

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 [13], 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. Figs. 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 a 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. Fig. 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. Fig. 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

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, The 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